

An Effective Framework for Life Cycle and Cost Assessment for Marine Vessels Aiming to Select Optimal Propulsion Systems

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Abstract

By adopting the concept of modularity, this paper introduced an optimal framework which facilitates life cycle assessment and life cycle cost assessment, thereby supporting rapid and reliable decision-making in the marine industry. The benefits of the proposed framework were discussed through two case studies where the optimal configurations of marine propulsion systems were determined from the economic and environmental perspectives. First, the performance of a short-route ferry using the hybrid system was compared with those of equivalent ships using diesel-electric and diesel-mechanical propulsion systems respectively. Research findings revealed the excellence of the hybrid system in both economic and environmental aspects. Second, the same method was applied to an offshore tug vessel to determine an optimal engine configuration. Results of analysis emphasised that the selection of multiple small-sized engines is more effective than two medium-sized engines. Both studies have proven that the proposed framework would be useful and practical for accelerating the life cycle analysis which allows ship designers and owners to obtain the long-term view of economic and environmental impacts for particular products or systems without demanding process. The paper also opened up the possibility of extending the application of the proposed framework to the areas where proper decision-making is essential but under-used.

Keywords: life cycle assessment, life cycle cost analysis, ship lifecycle design, modularity, hybrid ship

Symbol list

$EC_{main,i}$	energy consumption of scrapping/recycling material, I (kWh)
EI_t	environmental impact for any of GWP, AP, EP or POCP for each pollutant (kg)
FS_i	specific fuel oil consumption as a function of engine load, I (g/kWh)
LS	specific lubricant oil consumption (g/kWh)
$Mtr_{main,i}$	composition of material, i
N_e	normalization factor for any of GWP, AP, EP or POCP for each pollutant
P_i	engine load (%)
$RPr_{mat,i}$	recycling price of material, i (€)
T_i	time spent in each operating mode (years)
TEC_{main}	total energy consumption of main engine scrapping/recycling (kWh)
TRB_{main}	total recycling benefit of main engine (€)
$WC_{main,i}$	weight of material, I (kg)
C_e	amount of pollutant for the given time frame (kg)
C_{fc}	fuel price (€)
C_{lc}	lubricant price (€)

Abbreviations

AP	acidification potential
BWTS	ballast water treatment systems
CFD	computational fluid dynamics
CM	construction of main engine
DE	diesel-electric
DM	diesel-mechanical
DNV-GL	Det Norske Veritas (Norway) and Germanischer Lloyd (Germany)
DP	dynamic positioning
EP	eutrophication potential
Eurostat	European Community Statistical Office
GHG	greenhouse gas
GWP	global warming potential

HFO	heavy fuel oil
ICCT	The International Council on Clean Transportation
IMO	International Maritime Organization
ISO	International Organization for Standardization
LabVIEW	Laboratory Virtual Instrument Engineering Workbench
LCA	life cycle assessment
LCCA	life cycle cost assessment
LCIA	life cycle impact assessment
LO	lubricant oil
MM	maintenance of main engine
MARPOL	marine pollution
MDO	marine diesel oil
OM	operation of main engine
POCP	photochemical ozone creation potential
RoPax	roll-on-roll-off-passenger-ship/ferry
SFOC	specific fuel oil consumption
SLOC	specific lubricant consumption
SM	scrapping of main engine
SMEs	small and medium-sized entrepreneurs

1. Introduction

1.1. Background

As the world population continues to grow, globalisation has led to a remarkable growth in the sea-borne trade, which accounts for more than 80 % of global freight transport. The heavy-reliance on maritime transport has significantly contributed to exacerbating the marine pollution. In response to this fact, the ICCT (2011) predicted that greenhouse gas emissions from shipping activities will triple by 2050.

Such adverse environmental prospects have played as the driving force behind the introduction of a series of stringent maritime regulations aiming to curb the marine pollution from the world fleet (MARPOL, 2011). Those environmental regulations urge shipbuilders and marine engineers to strive to develop cleaner technologies, suggesting that the green shipping is one of the most urgent issues in the marine industry.

For instance, IMO has provided a series of guidelines as means to calculate, monitor and reduce greenhouse gas emission (IACS, 2013). Although the IMO's guidance is a simple and handy tool in estimating CO₂ emissions during the ship operations, there are still demands for estimating the holistic environmental impact of marine vessels in accordance with the lifecycle of those ships.

In addition to environmental issues, ship designers and owners have paid equal efforts to build/operate ships in cost-effective manners to survive in fierce market competition. Since numerous new systems and technologies are flooding the industry, proper decision-making among various options may be an essential process.

On the other hand, the current practice of analysing economic impacts of the marine vessels are somewhat biased by the short-term perspectives of stakeholders (Fuller, 2010). For example, ship-builders strive to reduce the costs of ship construction by selecting cheaper products or systems while disregarding the long-term cost-saving potentially achieved by relatively expensive ones.

1.2. Introduction to life cycle and cost assessment

From cradle to grave, a ship is engaged in various activities leading to spending money, consuming energy and producing emissions. In order to estimate the overall cost and the environmental impact of the vessel in question, the flows of cash, energy and emissions pertinent to every single ship activity in various life stages need to be tracked and analysed.

While the reliability of current practices on estimating economic and environmental impacts in the marine industry is perceived to be low, there have been demands for an enhanced approach which helps shifting our focus from a short-term view to a long-term one, thereby achieving proper decision making with higher reliability at the early design stage (Fuller, 2010).

In this context, LCA and LCCA have been proven useful to estimate the holistic economic and environmental impacts of particular products and/or systems (ISO, 2008). To support such analyses, several commercial software such as GaBi (2017), KCL-ECO, LCAiT, PEMS, SimaPro (2016) and TEAM have been introduced (Dašić et al., 2007). These software provide users modelling tools and solvers with the comprehensive database to estimate the environmental impact of particular items (Sharma and Weitz, 1995). Not surprisingly, a number of LCA and LCCA research in various industries have been implemented with the commercial software. Some examples are described here:

An LCA study associated with alkaline hydrogen fuel cell was carried out by Benjamin et al. (2013) aiming to find the impact of using gas atomised sponge nickel instead of cast and crush sponge nickel and platinum. A new LCA methodology for the construction phase is reported in Raugei et al. (2014). Duan et al. (2015) carried out a study in the field of urban transportation to determine the energy demand in their life cycle. A study carried out by Havukainen et al. (2017) dealt with assessing the environmental impact of municipal solid waste management incorporating a mechanical waste treatment with incineration for the specific site of Hangzhou, China. Esteve-Turrillas & Guardia (2017) conducted a life cycle assessment to compare the recovered cotton from recycled garments with cotton from traditional and organic crops. Pereira et al. (2017) applied LCA method to evaluate the carbon footprint during local visitors' travelling in Brazil using a route from Rio de Janeiro to Sao Paulo in their case study.

Noticeably, the automobile industry was one of the most proactive field in terms of LCA studies. There are some remarkable examples can be summarized as below:

In order to reduce the environmental impact during the life of a car Dhingra and Das (2014) applied LCA in the manufacturing industry. Delogu et al. (2016) carried out an environmental and economic life cycle assessment of a lightweight solution for an automotive component. They compared talc-filled and hollow glass microspheres-reinforced polymer composites. Their results stated that overall the end-of-life phase is not affected significantly due to weight reduction. Similarly, Raugei et al. (2015) carried out a coherent life cycle assessment of range of light weighting strategies for compact vehicles using advanced lightweight materials (Al, Mg and carbon fibre composites).

LCA and LCCA methods have also been applied to the shipbuilding industry in order to investigate the holistic cost and environmental impacts across ship design options.

Blanco-Davis and Zhou (2014) examined the economic-environmental effects of two different hull coating methods and three different types of BWTS. Ling-Chin et al. (2016) applied LCA method to a case study on evaluating the economic-environmental benefits of a hybrid power system on a Ro-Ro vessel. They concluded that the LCA was an effective process for proper decision making as it could aid evaluating the holistic impact on the environment, human beings and natural reserves. Also, a series of LCA and LCCA has been applied to a variety of other maritime-related researches. Ellingsen et al. (2002) have introduced an effective tool for ship design, and Fet and Michelsen (2000) have applied LCA to water-borne transportation systems. Ship retrofitting processes were explored in the LCA aspect by Koch et al. (2013). The technique of the LCA was also used for several purposes in the marine industry: particularly, to improve sustainable shipping (Utne, 2009); to investigate the benefits of the cleaner fuel application (Bengtsson et al., 2012); to optimize marine systems (Basurko and Mesbahi, 2012); and to enhance system engineering and management (Fet et al., 2013).

Some remarkable trends of recent LCA researches in the marine industry can be summarized as follows:

Rahman et al. (2016) carried out a life cycle assessment of steel in the ship recycling industry for Bangladesh. They compared different unit operations of steel scrap processing to evaluate their relative environmental impacts including GWP. Their findings showed that changes in cutting methods or use of protective gear during cutting process result in a significant decrease in local environmental and health impacts. Obrecht and Knez (2017) carried out a study to investigate carbon and resource savings

of different cargo container designs. Their findings revealed that the relatively small change in container design could have a significant impact on the whole life cycle of a cargo container since material use is the most intensive phase of a container's life cycle from an environmental perspective. Cucinotta et al. (2017) investigated the excellence of LCA to the yacht industry by carrying out a comparative case study for different yacht designs. Gilbert et al. (2018) carried out an assessment of full life-cycle air emissions of alternative shipping fuels such as LSHFO, MDO, LNG, LH2, Methanol, SVO Soy, SVO Rape, Biodiesel Soy and Biodiesel Rape.

Despite voluminous academic studies described above, the practical use of LCA and LCCA is still sparse in the marine industry. The under-use of such analyses in this field can be attributed to the complexity of those analyses which appear technically impossible to be carried out without commercial software supporting LCA and LCCA modelling and calculations in cooperation with the extensive database. Even with the aid of such software, the process of LCA and LCCA is still difficult and time-consuming as those carry many details and complexities behind simple results (McManus and Taylor, 2015). Therefore, the life cycle analyses are regarded as unwieldy tools that cannot be handled without experienced staff with the industry-specific lifecycle modelling skills and associated knowledge. In particular, such laborious works have been practically not admissible to the marine industry where rapid but appropriate decision-making always matters.

Given this background, this paper has been tailored to the needs of naval architects, shipyards and ship-owners who endeavour to construct/operate/manage ships in optimal manners.

1.3. Research objective and outlines

The fundamental objective of this paper is to introduce an optimal framework to promote LCA and LCCA in the marine industry. The proposed framework was aimed as a simple, but credible approach to help rapid decision-making in determining the best option out of various choices regarding cost and environmental impacts in the long-run.

To achieve this goal, Section 2 describes the general principle and process outlines of the optimal framework, whereas Section 3 specifies the application of the proposed structure into marine propulsion systems. Following this, in Section 4, the excellence of the proposed approach is evidenced by two case studies which have been currently issued by shipyards and

ship-owners; the first case study is to investigate the advantages of battery usage in a short-route hybrid ship while the second one is to determine the optimal engine configuration for an offshore tug vessel. Research findings are discussed in Section 5, and key results are, finally, highlighted and summarized in Section 6.

2. Optimal framework for rapid life cycle and cost analysis

Fig. 1 shows the proposed framework which was born to promote and facilitate the LCA and LCCA for marine vessels. The context is combined with three stages: (1) modularity of ship life cycle, (2) encapsulation of LCA and LCCA algorithm into modules and (3) analysis and decision-making.

2.1. *Modularity of ship life cycle*

The concept of '*modularity*' is typically used for designs in which the overall system is divided into small pieces, called '*modules*' that can function individually or be combined with other modules according to designers' preferences (Ulrich, 1995). Modular designs have been widely applied in shipbuilding where there are specific parts of products to be added or removed without changing the rest of the system (Pero et al., 2015). This paper presents a new application of the modularity for developing the optimal LCA and LCCA framework.

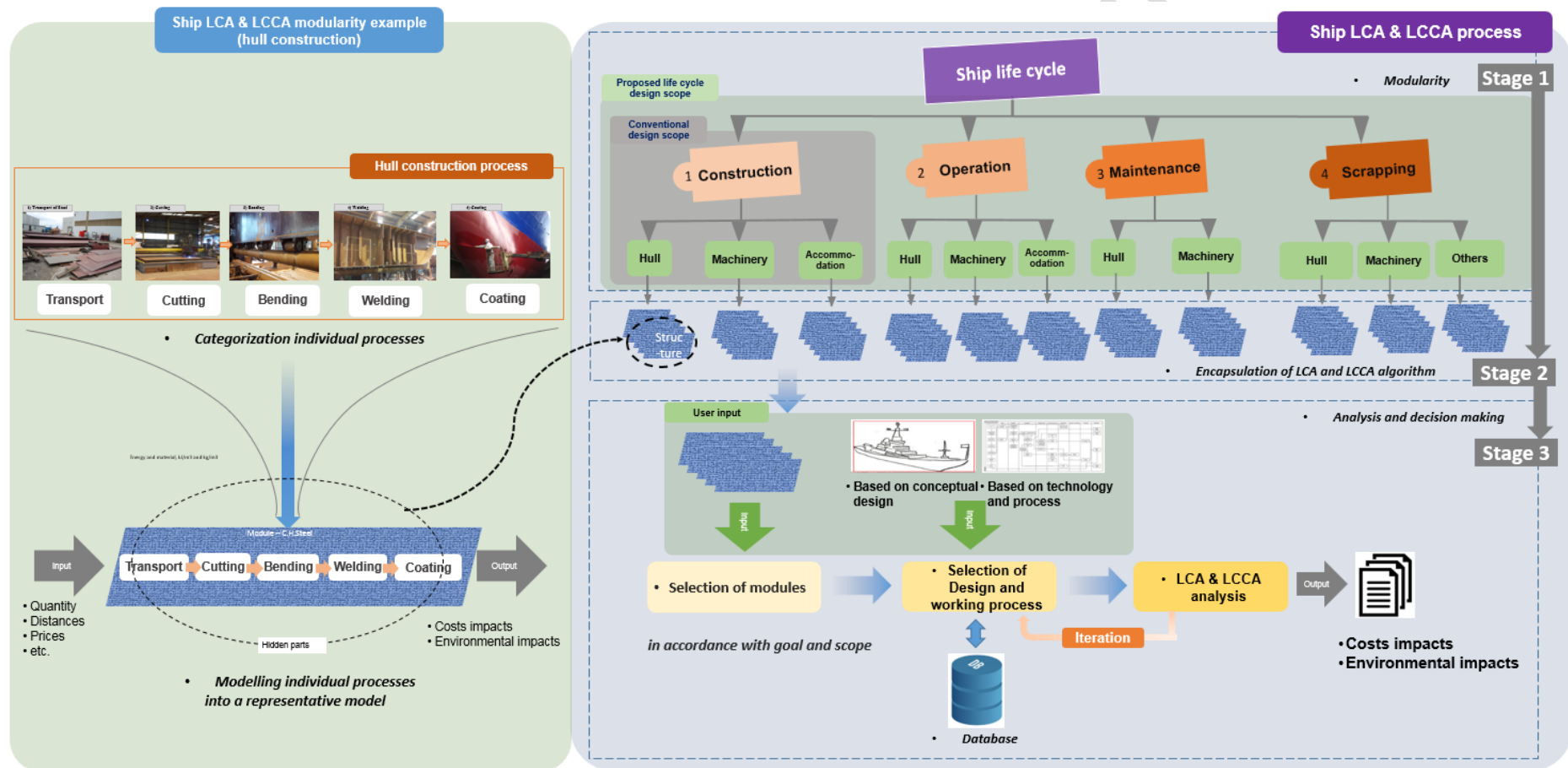


Fig. 1. Structure of proposed life cycle design process.

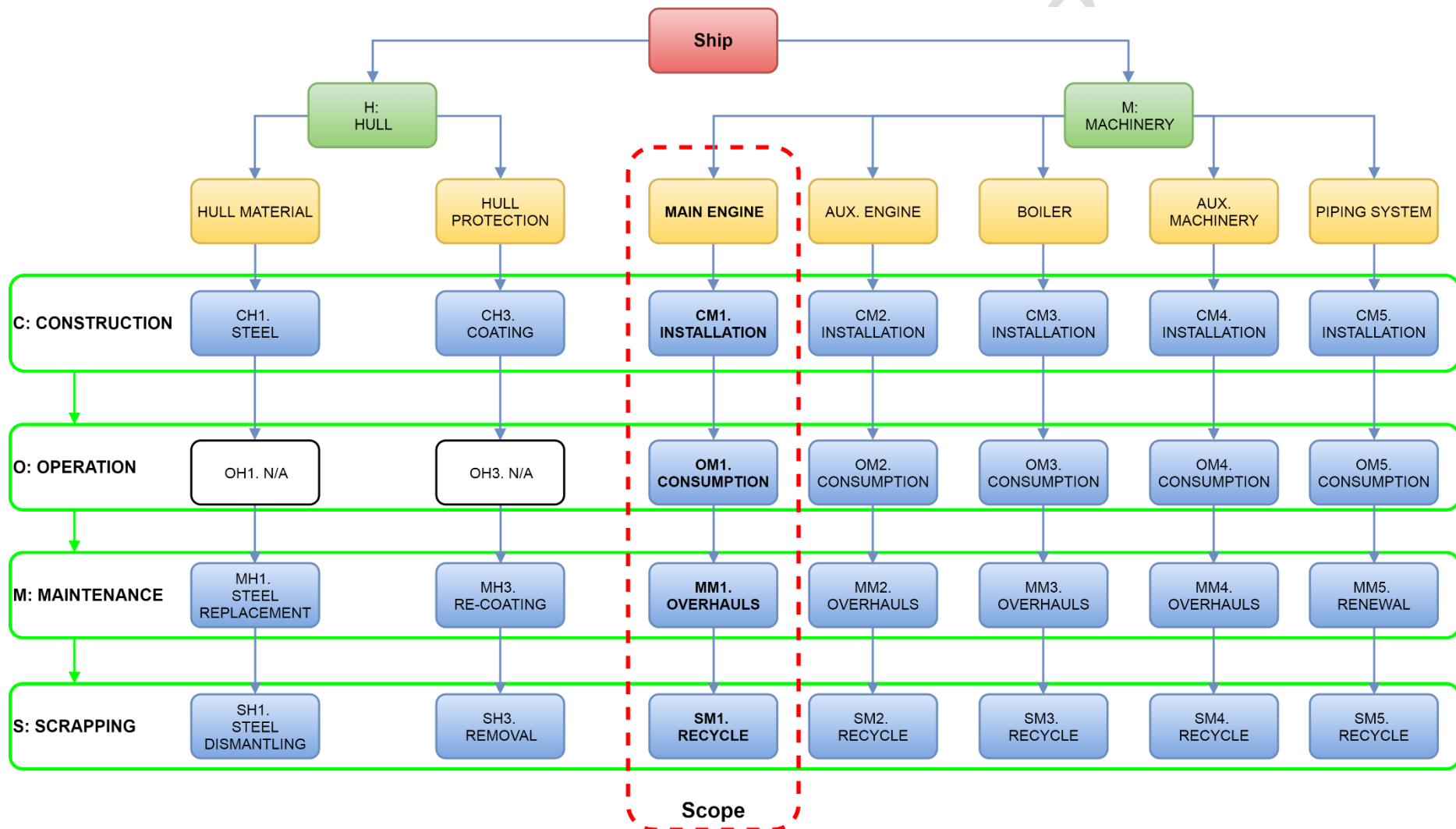


Fig. 2. Modularity of ship consistent with ship life cycle process.

Fig. 2 shows the structured modularity consistent with the ship lifecycle process. Concerning this, the entire ship is broken down into primary parts, such as hull and machinery. The primary parts are then sub-divided into secondary parts equivalent to material/product levels. Given that a ship is subjected to four representative life stages - construction, operation, maintenance and scrapping (Jivén et al., 2004), this framework assigns the secondary parts into each stage of ship lifecycle. Individual parts of the ship in accord with various life stages is, then, formulated as a module.

The principle of modularity applied in this paper is to integrate all individual processes belonging to a particular part of a ship into a single representative module. In the same way, multiple prototypical modules according to the processes involved in different levels of ship life cycle stages can be developed. For example, the module of “CH1 Steel” represents all the activities associated with steel - a major material for ship construction - at hull construction stage; “CH1 Steel” involves several sequential processes such as material production, transportation, cutting, bending, welding, and assembling as shown in Fig. 3. In this way, all other ship processes are identified and, then, assigned into equivalent modules across the ship life stages.

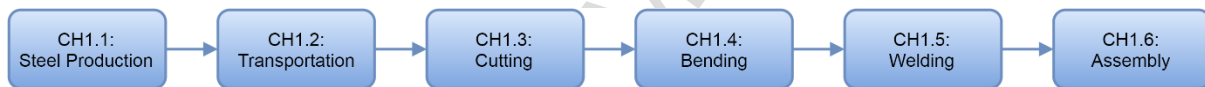


Fig. 3. The process flow of steel for ship hull at construction stage.

2.2. Encapsulation of LCA and LCCA algorithm into modules

Analytic formulations for LCA and LCCA are, then, encapsulated in individual modules, which interacts with a database having the various process data in different stages and parts regarding energy consumption, emission production and costs, collected from a variety of resources such as shipyards, product manufactures, literature, etc.

The algorithm for LCA and LCCA written in the modules has referred to a generic LCA process described in ISO Standards 14040 (2006a) and 14044 (2006b) and modified accordingly.

2.2.1. LCA

To investigate the environmental impacts, the LCA written in the modules estimate four major pollution potentials: GWP, AP, EP and POCP. Also, a list of major contributors to increasing

those potentials were identified and intended to be quantified accordingly. Different impact factors (or normalisation factor) described in Table 1 are applied to each pollutant based on the guidelines of CML 2016 (GaBi, 2017).

Table 1

Type of representative pollutants and their impact factors.

Type of Pollutant	Symbol	GWP (kg CO ₂ equiv.)	AP (kg SO ₂ equiv.)	EP (kg PO ₄ equiv.)	POCP (kg C ₂ H ₄ equiv.)
Ammonia [to air]	NH ₃	×	1.6	0.35	×
Ammonia [to fresh water]		×	×	0.35	×
Ammonia [to sea water]		×	×	0.35	×
Carbon dioxide	CO ₂	1.0	×	×	×
Carbon monoxide	CO	0.027	×	×	0.027
Chemical oxygen demand [to sea water]	COD	×	×	0.022	×
Chemical oxygen demand [to fresh water]		×	×	0.022	×
Dinitrogen oxide	N ₂ O ₃	265.0	×	0.27	×
Ethane	C ₂ H ₆	×	×	×	0.123
Ethene [ethylene]	C ₂ H ₄	×	×	×	1.0
Hydrogen chloride	HCL	×	0.749	×	×
Methane	CH ₄	25.0	×	×	0.006
Nitrogen oxides	NO _x	×	0.5	0.13	0.028
Phosphate	PO ₄	×	×	1.0	×
Sulphur dioxide	SO ₂	×	1.2	×	0.048
Toluene	C ₇ H ₈	×	×	×	0.637

According to Eq. (1), the quantity of pollutants calculated from the LCA modules in the typical ship lifecycle stages is multiplied by the impact factors, thereby their contributions to the different environmental categories are evaluated (Wang et al., 2017). This formula is shown below.

$$EI_t = \epsilon_e \cdot N_e \quad (1)$$

2.2.2. LCCA

In the same line with the representative ship life cycle stages, the life cycle cost for a particular part of the ship, *i*, is categorised into construction costs (initial costs), $C_{C,i}$, operation costs, $C_{O,i}$, maintenance costs, $C_{M,i}$, and Scrapping costs, $C_{S,i}$ (Niekamp et al. 2015). Therefore, the overall lifecycle cost, LCC, can be expressed as the sum of all costs for the relevant parts of the ship at different stages, as shown in Eq. (2).

$$LCC = \sum_{i=1}^n C_{C,i} + \sum_{i=1}^n C_{O,i} + \sum_{i=1}^n C_{M,i} + \sum_{i=1}^n C_{S,i} \quad (2)$$

2.3. Analysis and decision-making

The built-in algorithms of LCA and LCCA in individual modules allow any single module becomes entirely independent of other modules. Hence, users can select any single module or multiple modules according to their work scope and immediately acquire the results without any unwieldy modelling.

Based on the platforms described in sections 2.1 and 2.2, the LCA and LCCA process can begin by selecting the relevant modules and entering the appropriate data/information according to their goals and scope. The life cycle results are expressed by the combination of the individual results calculated for each applied module. It is, then, presented in the form of information on holistic ship life costs and environmental impacts. The analysis can be iterative by entering different design or process parameters. Therefore, the optimised design option can be determined in consideration of the various results of candidate design options.

To carry out case studies, Fig. 4 specifies the modules for marine propulsion system (main engines), describing the modules within the red-dotted line in Fig. 2. This figure may also present a clear explanation of the scope and boundaries for the case studies that will be carried out in the sections to follow. This platform is, then, implemented in an in-house program written in LabVIEW, providing the built-in platform to estimate the flows of energy and emissions for LCA and the cash flow for LCCA.

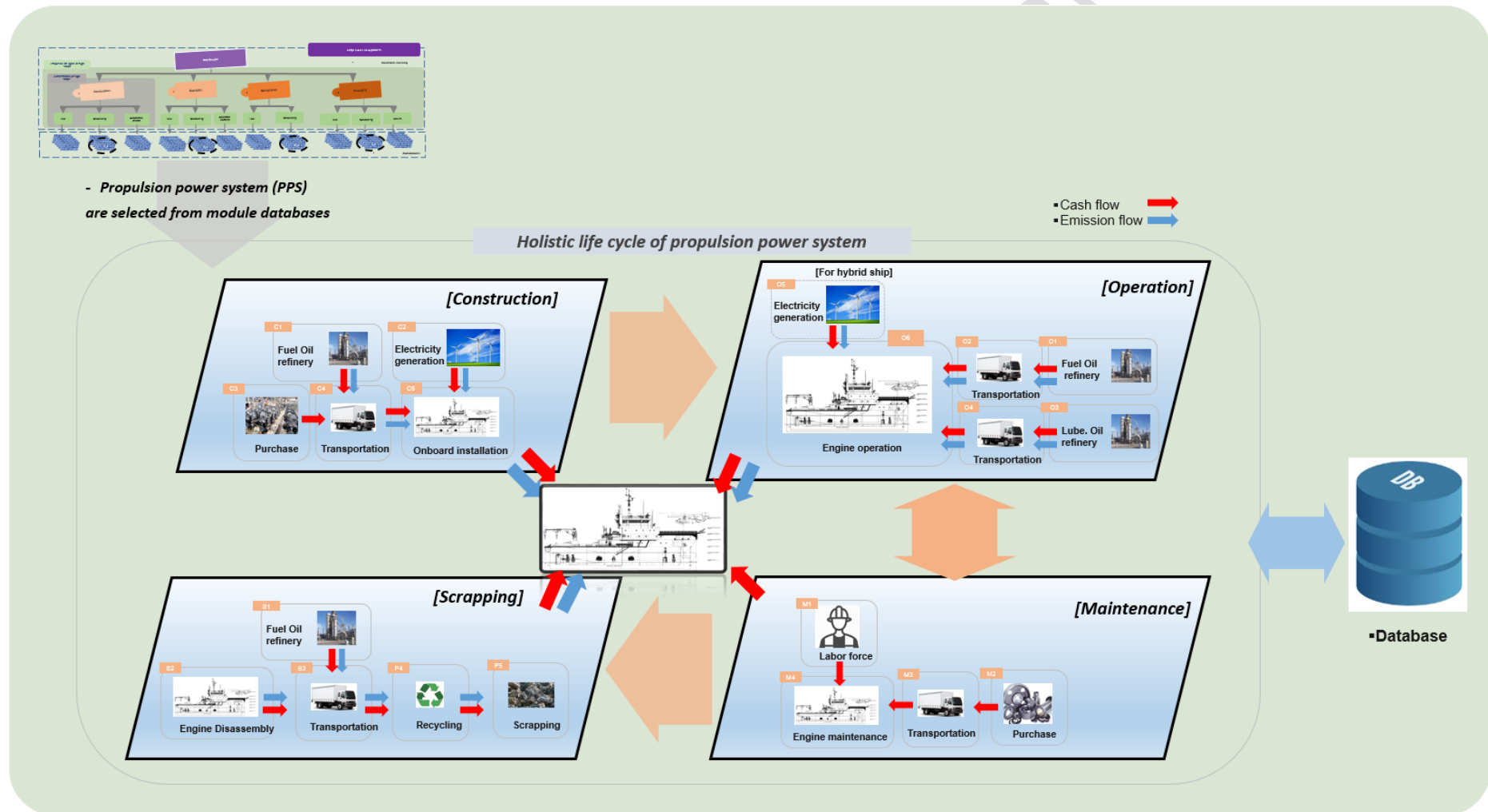


Fig. 4. Lifecycle modules for propulsion power system.

2.4. CM1: main engine module at construction stage

This module represents the construction processes of the main engine, which begins with the production purchase at the factory, transportation to the shipyard, thereby being completed with the onboard installation. These primary processes also associate subsequent processes: fuel production at the refinery, fuel consumption for transportation as well as electricity generation at power plants and its consumption for onboard installation. Fig. 5 outlines the construction processes for main engine system with major input and output parameters.

The algorithm of LCA and LCCA fitted in this module incorporates user-input parameters such as price information for products, fuels and energies; information for product specifications such as capacity and weight, shipping distance. Based on this platform, energy consumption, emissions and costs for each process in this module are calculated.

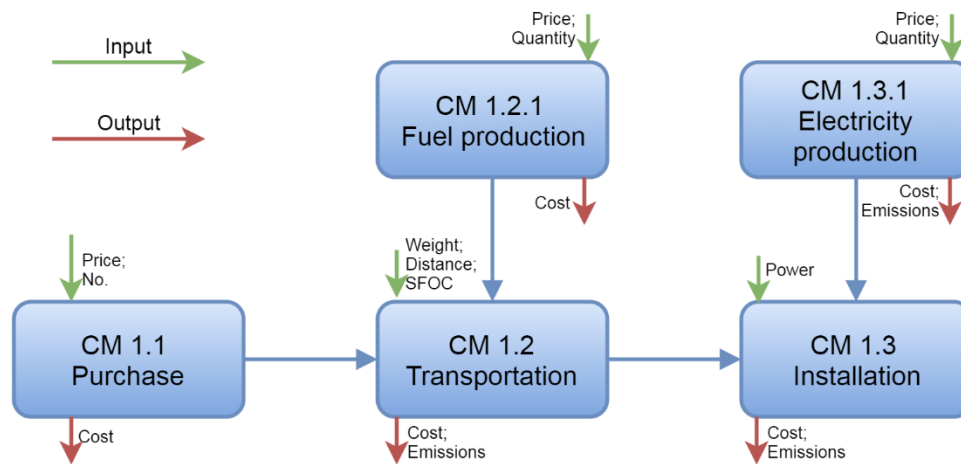


Fig. 5. Construction processes for main engine system.

2.5. OM1: main engine module at operation stage

The activity of main engine system at ship operation stage is mainly to generate propulsion power to steer the ship by consuming fuels and lubricants. In this regard, the processes engraved in this module is more or less related to their production, transportation and onboard consumption as illustrated in Fig. 6.

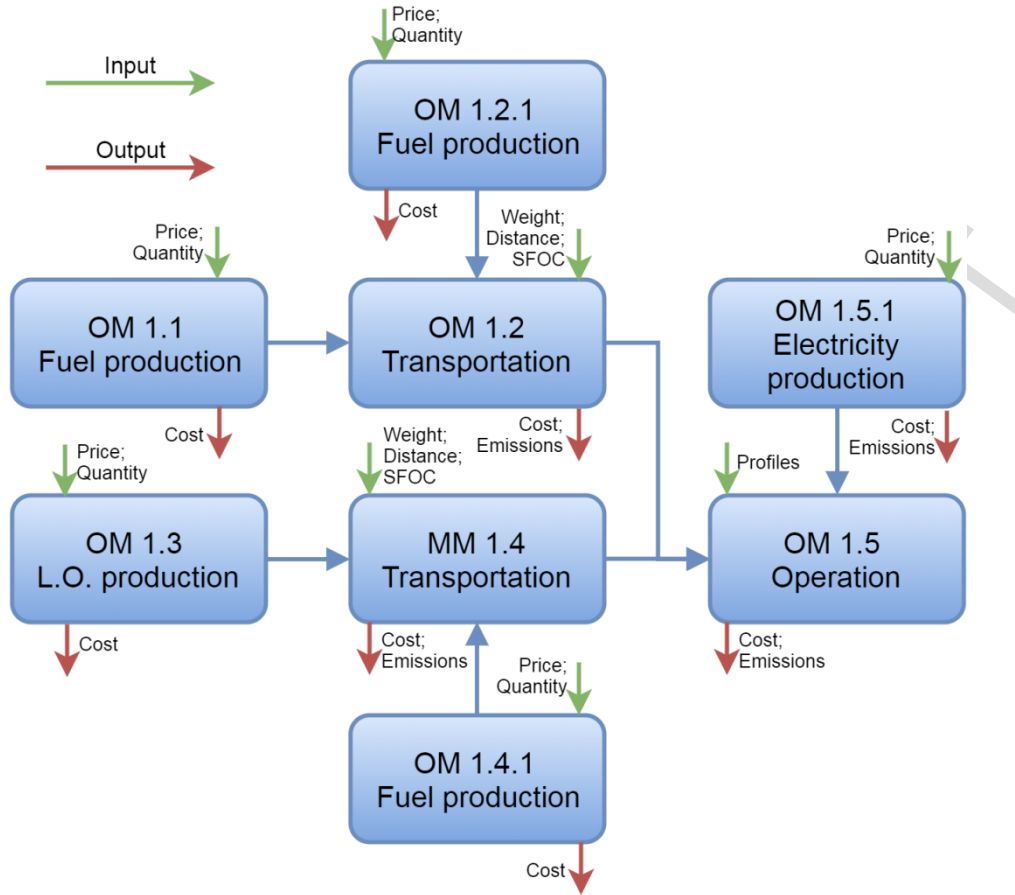


Fig. 6. Operation processes for main engine system.

By using the Eqs. (3-6), the fuel consumption and economic expenses can be estimated according to the engine specifications combined with ship operating profiles that specify engine loads at particular ship speeds and time spent. For Eq. (3), the SFOC was driven from the standard SFOC curves for 2-stroke and 4-stroke engines (Lindstad and Sandaas, 2016).

Similarly, using the fuel-based factors listed in

Table 2, potential pollutants from the fuel burnt in the main engine can be quantified (Carlton et al., 1995; Alkaner and Zhou, 2006).

$$F_c = \sum_{i=1}^n FS_i \times P_i \times T_i \quad (3)$$

$$C_F = \epsilon_{fc} \cdot F_c \quad (4)$$

$$L = \sum_{i=1}^n LS \times P_i \times T_i \quad (5)$$

$$C_L = \epsilon_{lc} \cdot L \quad (6)$$

Table 2

Emission factors for marine diesel engine operation.

Engine Emission		Fuel-based factor (tonnes /fuel-ton)
NO _x	Inorganic emissions to air	0.057
CO		0.0074
CH ₄		0.0024
CO ₂		3.170
SO _x		0.02 (=20×(1.0)%S content)

2.6. *MM1: main engine module at maintenance stage*

A main engine is comprised of several parts that are required for regular maintenance according to the instructions of the engine manufacturer so that they can keep operating as designed. This module reflects activities associated with engine maintenance including engine overhaul, inspection, repair, and part replacements. The outline of the module is described in Fig. 7. In addition to day-to-day checks, various uptime-based maintenance, such as 200 to 100,000 hours, is performed. Table 3 lists typical engine maintenance intervals and the ratio of spare costs to engine costs (MAN Diesel & Turbo, 2011). Engine running hours and consequent maintenance costs are estimated based on proposed engine operating profiles.

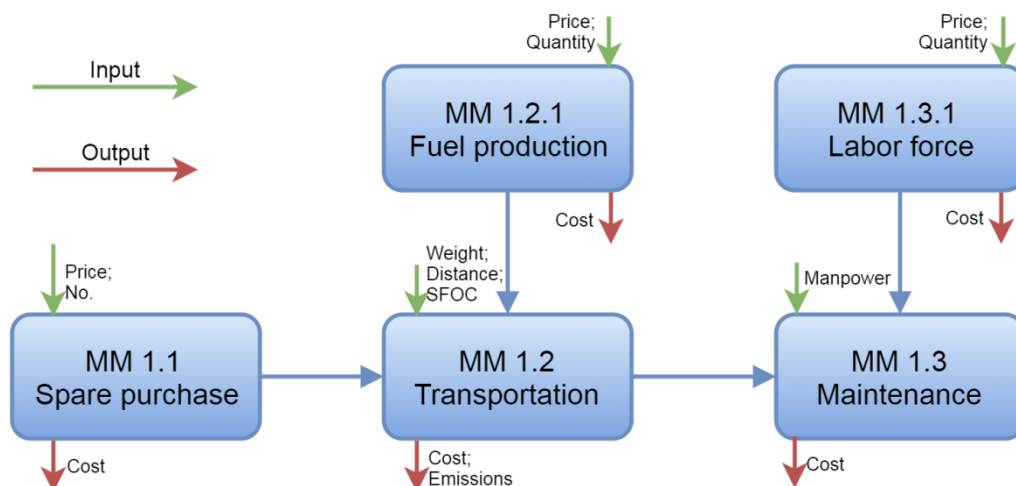
**Fig. 7.** Maintenance processes for main engine.

Table 3Typically-small four stroke engine maintenance plan (*by courtesy of MAN Diesel & Turbo*).

Interval (hours)	Major works	Working time (hours)	Spares to be renewed	Spare cost ratio to engine costs
Daily	Daily Maintenance Work -Clean engine exterior of plant debris -Check engine exterior for oil- and coolant leaks -Check coolant level and oil level -Service air filter -Drain water from additional fuel filter	0.4	-	-
200	Checking of: -Engine exterior for loss of oil and coolant -Coolant level -Concentration of antifreeze / anticorrosion agents -Engine oil level -Engine alarms, emergency stop device, over-speed protection -Functioning of instruments -Coolant preheating, function, setting -Coolant hoses for leaks -Fuel lines for leaks -V-belt tension, retightening if necessary V-belt(s) -Draining water from auxiliary fuel filter -Water hose clamps, pipe connections and bolts for security, -retightening if necessary Cleaning of: -Fuel pre-filter Test run Changing of: -Servicing the air cleaner	2.75	-	-
400	Checking of: -Retightening of cylinder head bolts -Valve clearance, setting if necessary Changing of: -Engine oil -Engine oil cartridge(s)	4.20	-Oil changes	0.09 %
1,200	Changing of: -Fuel filter	0.50	- spin on oil filter - seal ring - Fuel filter cartridge - Spin on fuel filter - Valve cover gasket	1.67 %
4,000	Checking of: -V-belt idler pulley, replacing if necessary -Clearance of engine water pump bearing -Fan bearing clearance	1.30	-	-
6,000	Checking of: -Injectors, replacing if necessary -Compressions pressure	4.00	- v-belt - injection nozzle - seal ring - air cleaner cartridge Micro-station - filler cap	5.29 %
10,000	-Replace coolant -Check injection pump -Replace injectors -Replace turbocharger -Replace bearing fan and belt pulley -Overhaul of water pump -Overhaul of alternator and starter	30	- Repair kit for water pump - Rubber hose - Corrugated hose - Injectors - Turbocharger - Bearing fan - Belt pulley	49.21 %
20,000	-Replace liners -Replace connecting rod bearing -Replace piston rings -Overhaul cylinder heads	40	- Connecting rod bearing - Keystone ring - Taper Face Compressing ring - Bevelled oil Scraper Ring - Cylinder liners - Alternator	20.75 %

			- Starter	
40,000	-Replace pistons -Replace crankshaft bearings -Replace valve gear -Measure camshaft -Measure crankshaft	70	- Pistons - Crankshaft main bearings - Thrust bearing - Valve guide intake - Valve guide exhaust	47.4 %

On the other hand, the environmental impacts associated with the production and transport of marine engine spare parts during the maintenance phase are disregarded in this prototype module. It is because the range of environmental impacts at this stage is negligibly small, while data collection may be impracticably demanding (Oguz et al., 2017).

2.7. SM1: main engine module at scrapping stage

This module represents activities of the system end-of-life, which the wearing system disassembly at ship dock, transportation, recycling and scrapping at a relevant facility as outlined in Fig. 8.

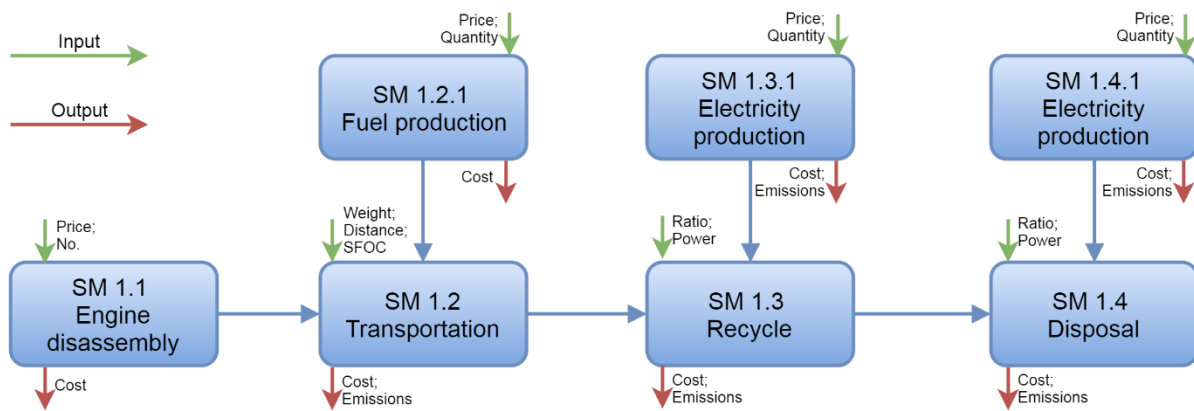


Fig. 8. Scrapping processes for the main engine.

Table 4 presents the general ratios of material contents for marine engines; steel and cast iron account for substantial parts of the engines while small portions of aluminium, copper, zinc, lead and nickel are also listed in engine compositions (Scania, 2016). Through a series of processes, components of materials are to be recycled for reproducing steel and cast iron, whereas the rest are to be disposed by landfilling or incineration. The required energy and produced emissions for recycling processes are determined by a number of researchers as shown in Table 5 (Ling-Chin and Roskilly, 2016).

Table 4

Material content of typical marine engine (Scania, 2016).

Engine Material	Weight ratio (%)
Steel	40.0
Cast iron	46.0
Aluminium [Al]	8.0
Copper [Cu] and Zinc [Zn]	0.2
Lead [Pb]	0.1
Plastic	0.9
Rubber	0.9
Paints	0.9
Oils and Grease	3.0
Total	100.0

Table 5

Energy and material required, and emission released for material recycling (Ling-Chin and Roskilly, 2016).

Item			Steel and cast iron	Stainless steel	Al	Cu	Zn	Pb	Ni
Key references			(Yellishetty et al., 2011; Norgate, 2014)	(Crundwell et al., 2011)	(Gaustad et al., 2012; Paraskevas et al., 2015)	(Muchova et al., 2011; EEA, 2013)	(Gordon et al., 2003)	(Genaidy et al., 2009)	(Reck et al., 2008)
Energy	MJ	Electricity	1.71	7.18	0.10	-	0.73	-	1.92
		Natural gas	0.62	2.60	10.22	-	0.34	-	2.30
		Coal	-	-	-	-	1.46	-	1.71
		Blast furnace gas	-	-	-	4.95	-	7.00	-
		Heavy fuel	-	-	-	-	-	-	0.22
Material	kg	Pig iron	0.02	0.06	-	-	-	-	-
		Oxygen (l)	0.04	0.17	-	-	-	-	-
Emission	Kg	SO ₂	1.02E-04	4.28E-04	4.41E-03	2.00E-05	3.67E-03	2.00E-05	-
		NO _x	2.40E-04	5.27E-06	2.65E-03	7.00E-05	1.57E-03	7.00E-05	-

		CO ₂	1.05E-01	4.41E-01	5.45E-01	2.00E-01	-	2.00E-01	1.19E-02
		CO	2.40E-03	1.01E-02	8.83E-04	1.50E-05	-	1.50E-04	-
		PM2.5	1.59E-02	6.71E-02	8.83E-04	1.90E-04	3.94E-05	7.90E-03	2.95E-04
		PM10	2.01E-04	8.46E-04	-	2.60E-04	7.56E-06	1.06E-02	4.29E-05

Table 6 shows the economic benefits from the material recycling in accord with the market prices (ScrapSales, 2017). Therefore, total energy consumption of the main engine scrapping/recycling and total recycling benefit of the main engine are calculated through Eqs (7-8) respectively.

Table 6

The benefits of recycling (ScrapSales, 2017).

Metal type	Scrap metal price (€ / kg)
Copper	2.60 – 3.60
Aluminium	0.25 – 1.50
Lead	0.42 – 1.00
Brass	0.90 – 2.80
Copper Wire	3.60 – 3.90
Steel (Heavy)	0.05 – 0.14
Steel (Stainless)	0.55 – 1.00
Iron	0.04 – 0.08
Titanium	1.40 – 2.00
Gold	8,800 – 23,460
Silver	130 – 260
Platinum	20,140 – 22,360

$$TEC_{main} = \sum_{i=1}^n EC_{main,i} \quad (7)$$

$$TRB_{main} = \sum_{i=1}^n (RPr_{main,i} \times WC_{main,i}) \quad (8)$$

3. Case study

3.1. Study outlines

The proposed ideas discussed in section 2 and the modules developed in section 3 are applied to two different case studies on investigating the optimal selection of marine propulsion systems, according to industrial requests.

- Case study 1: Comparison of a hybrid propulsion system to conventional diesel-electric and diesel-mechanical ones for a short-route ferry
- Case study 2: Comparison between two different engine configurations devised in early design stages for an offshore tug vessel

The process of the LCA and LCCA begins with setting up input parameters in the user interface. A number of input parameters are placed in different parts and stages of ship lifecycle. A simple example can be shown in Fig. 9. For specifying the engine data in order to calculate LCA and LCCA, users are supposed to input several parametric values in a table format. Some parameters can be determined by referring to the database or some others can be made based on their own specific-conditions. Once all input data is put, the LCA and LCCA is calculated in accordance with the algorithm discussed throughout Section 2.

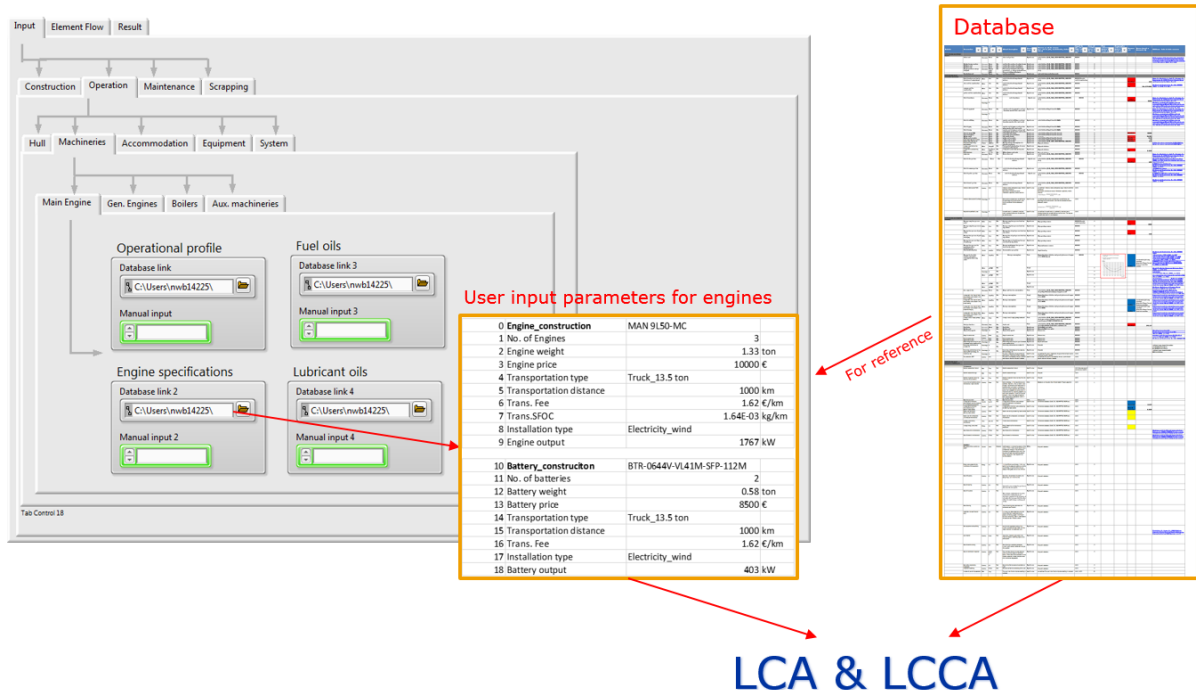


Fig. 9. Example of input parameters in LabVIEW Interface.

Based on various sources and common industry knowledge, the following information was used as the default inputs and conditions for case studies:

- Industrial electricity is generated from the wind power since the service area of the case ships 1 is the coast of Scotland where wind power plants provide most of nation's electricity (Murray, 2017). Nevertheless, the sensitivity of the electricity production across various energy sources on the environmental impacts will be discussed in the sensitivity analysis.
- The travel distances are considered as 1,000 km for new products to shipyards and 500 km for product disposal based on experts' judgement.
- Market prices are directly used for the following items;
 - Marine diesel oil (MDO) price: 290.58 € / ton (Bunkerworld Prices, 2017)
 - Lubricant price: 1681 € / ton (Bunkerworld Prices, 2017)
 - Transportation cost: 1.615 € / ton-km (Freightex, 2017)
 - Electricity: 0.119 € / kWh (0.041 € / MJ) at day time and 0.07 € / kWh (0.019 € / MJ) at night time (Scottish power, 2015; Eurostate, 2017)
 - Natural gas: 0.009 € / MJ (Eurostat, 2017)
 - Cost for the fuel consumed for transportation = 1,350 € / transport-ton (GaBi, 2017)
- Following information are borrowed from database linked to the commercial software, GaBi (GaBi, 2017).
 - Emission calculation method for transportation process, which is determined by the functions of travelling distances and fuel sources.
 - Emission data from producing the fuels and lubricants at refineries and from transportation means.
 - Electricity consumption for onboard installation and scrapping for a product
- The lifetime of case ships is in the range of 0 to 31 years, 0 is the construction stage, 1 to 30 for operation and maintenance, and 31 for scrapping stage (Shippipedia, 2013).
- According to the manufacturer's manual, batteries and other electrical parts for the hybrid ship are considered maintenance-free (Saft, 2017).
- Based on the current ship operators' practice in accord with environmental regulations, diesel engines are considered to run on MDO with a sulphur content of 1.0% (IMO, 2015).

- On the other hand, the SLOC is uniformly applied to 0.65g / kWh according to the instructions of an engine manufacturer (MAN Diesel & Turbo, 2011).
- Labor costs are only applied to maintenance phase and assumed to be 30 € / hour based on the European labour market (Eurostat, 2017).
- For battery recycling, a lithium-ion battery system consists of approximately 15% aluminium, 15% copper, 2% nickel and 2% stainless steel, and other materials are considered to be disposable in response to the manufacturer's manual (Saft, 2014).

An example of emission types and quantities

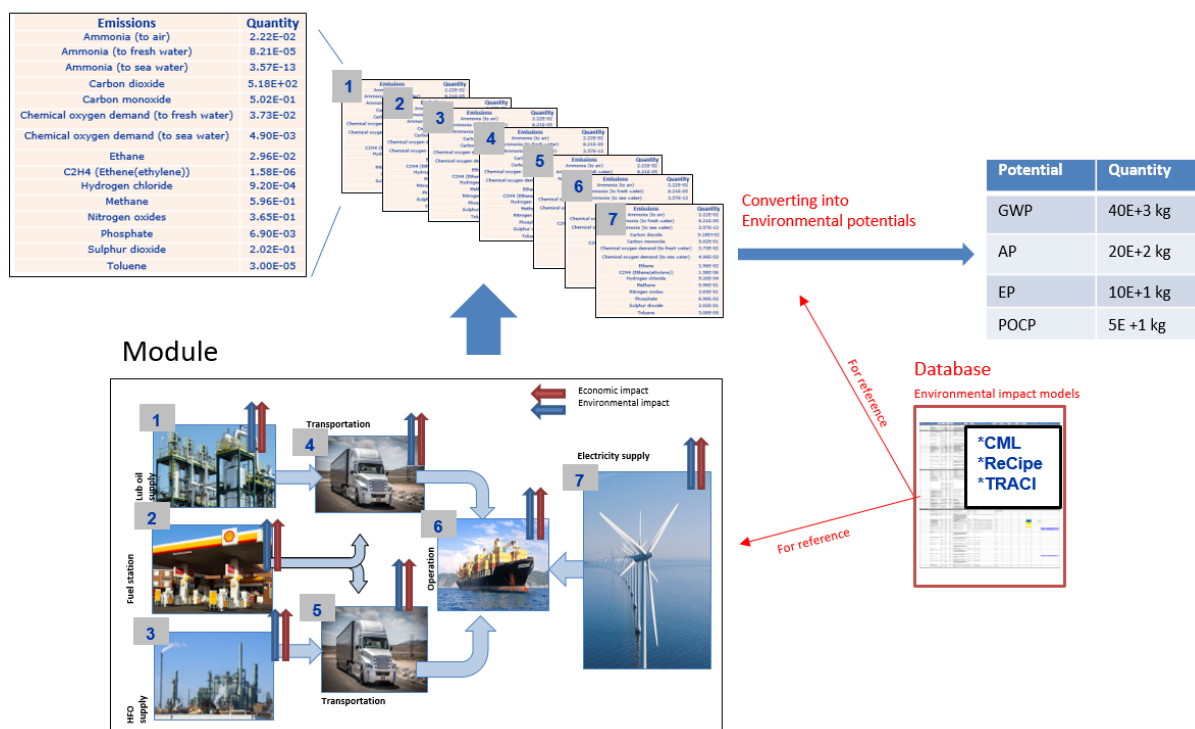


Fig. 10 shows an example outline for calculating environmental impacts associated with diesel engines at ship operation phase. Emissions from individual processes in this module were analysed based on user input parameters and environmental data driven from the database. For instance, the types and quantities of emissions produced from the process 1 - lubricating oil refinery process - were obtained from the database where emission data was stored across various ship activities. The same approach was taken for the other processes 2-7. As the result, types and quantities of emissions produced from individual processes were estimated. They were integrated, then, converted into several environmental potentials such as GWP, AP, EP and POCP in accordance with life cycle impact models, (such as CML, ReCipe and TRACI) that offers the insight into the relationship of emissions with those potentials. Such emission data were largely adopted from the Gabi database (Gabi, 2017).

An example of emission types and quantities

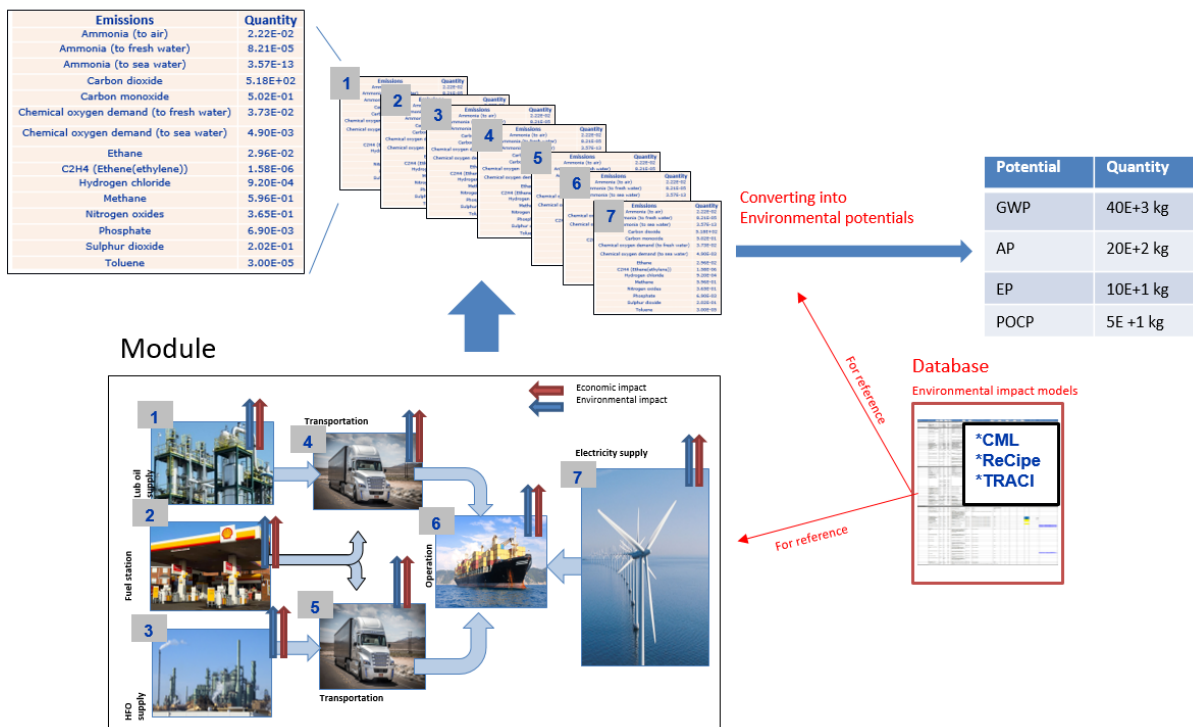


Fig. 10. Outline of emission analysis.

Given such characteristics of engine running hours and maintenance intervals, the LCA and LCCA have been carried out in aids of the LCA module programmed in the LabVIEW environment as described in Fig. 11. LCCA follows the same approach.

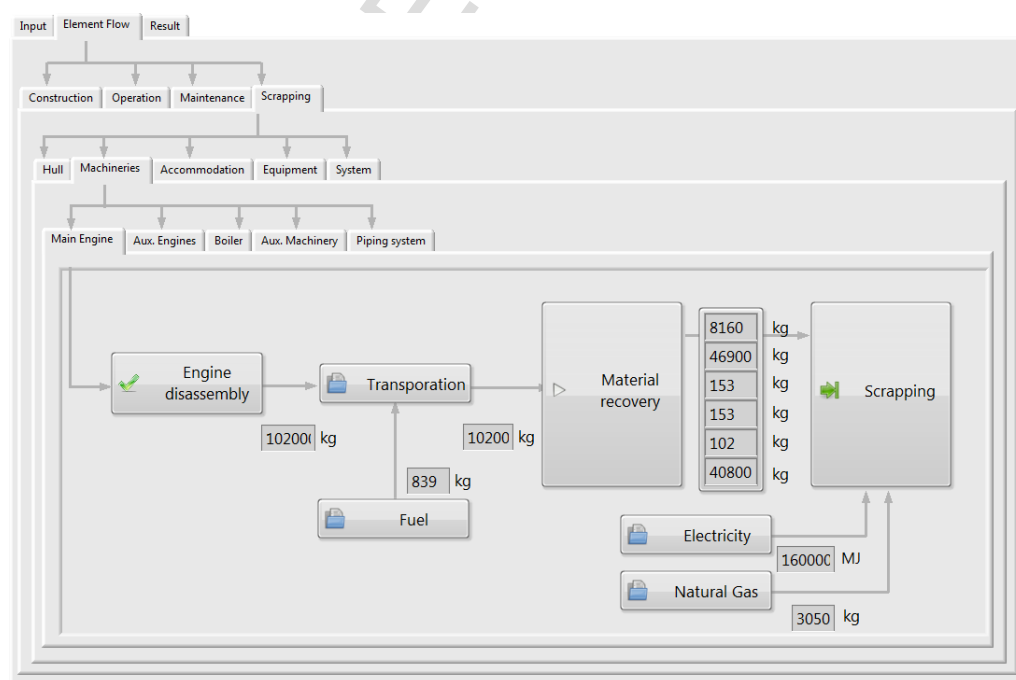


Fig. 11. Example of LCA based on the modules in LabVIEW Interface.

3.2. Case study 1: hybrid ships

Since the technology of lithium-ion batteries has been remarkably upgraded in the last few years, marine applications of such electric storage systems have become viable options (DNV GL, 2015). Consequently, it has led to the advent of hybrid ships that can derive propulsion power through either a fueled source (such as a diesel engine) or stored energy sources (batteries) (Ferguson Marine, 2016).

There have been a few studies on the feasibility of hybrid ships. As an example, Kavli et al. (2017) carried out a comparative study on the design of an environmentally friendly RoPax ferry using CFD. Their findings showed the importance of the hybrid system in decreasing the GHG emissions, suggesting future works for investigating the optimal usage of hybrid system in terms of minimizing air pollution.

However, the marine industry is still in its early stage of battery-powered ships (Shanhan, 2015). To achieve significant market penetration, it needs to demonstrate the excellence of hybrid vessels in various sectors, particularly concerning economy and environment-friendliness, compared to other existing propulsion types: DE and DM systems.


3.2.1. Case ship

The specification of the case ship, a hybrid Ro-Pax ferry, is presented in Table 7. For the purpose of comparison, the DM and DE systems are imaginarily applied to the case ship; since the vast majority of ships are equipped with DM or DE systems, it would be a credible comparison.

For the DM system, the engine configuration is to have two sets of 450 kW main engines, each of which is connected directly to the propeller shaft. Meanwhile, the DE system consists of three 360 kW diesel generators used to drive the electric motors connected to the propulsion systems. Based on the engine configuration of the DE system, the hybrid ship is additionally fitted with two sets of lithium-ion batteries which can share the electric loads with the onboard diesel engines. Fig. 12 compares the layout of a hybrid system to those of conventional DE and DM systems (Ferguson Marine, 2016).

Table 7

Specification of case ship.



Length × Breadth × Depth	39.99 m × 12.2 m × 1.73 m		
Displacement (t)	100 tons (Steel)		
Engine configuration	Hybrid (Actual)	Alternative 1 (DE)	Alternative 2 (DM)
	360 kW × 3 sets (3.2 tons) + 350 kW lithium-ion battery × 2 sets (3.5 tons)	360 kW × 3 sets (3.2 tons)	450 kW × 2 sets (4 tons)

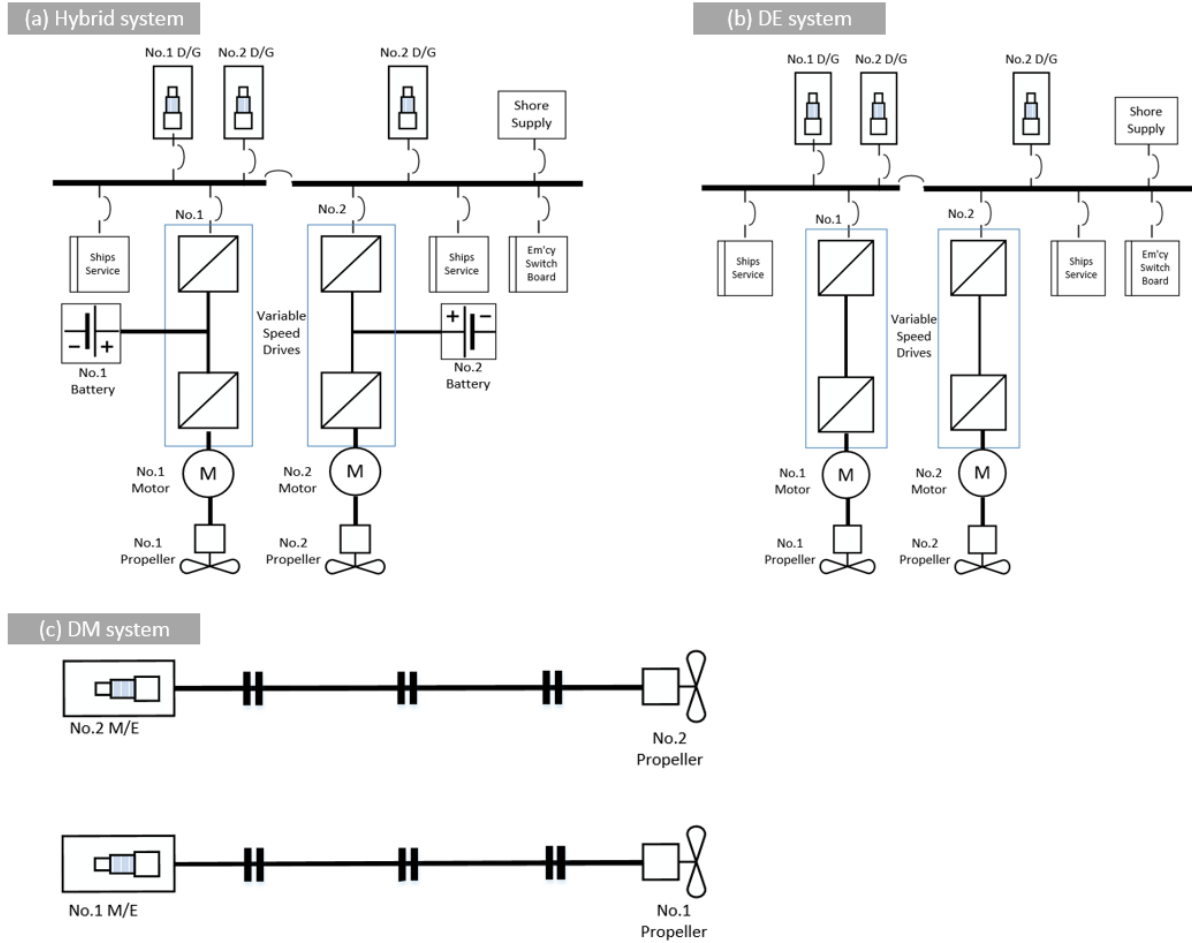


Fig. 12. Drawing for various propulsion systems (Ferguson Marine, 2016).

For construction phase, MAN Diesel and Turbo Ltd., engine prices were estimated at € 29,880 for a 360 kW engine set and € 37,350 for a 450 kW engine set by courtesy of the engine manufacturer (*direct contacted to the sales department*). According to the information provided by Ferguson Marine Ltd., batteries were costed at € 240 / kWh and the weight of which was calculated based on a factor of 0.1 kWh / kg. Given the ship having a regular voyage schedule, the current operational frequency of the case ship was approximately 20 trips daily from Sconser to Raasay in North Scotland at an average speed of 9 knots. The daily operation profile is allocated to 6 hours for transiting, 0.6 hours for manoeuvring, 3.72 hours at slip and 13.68 hours in port. According to the voyage report, the subject ferry is scheduled to be engaged in service for 313 days a year while 52 days are out of service for maintenance and vacation (Ferguson marine, 2016).

As the operating principle of the ship operators, the onboard batteries are charged by an onshore electric power supply facility overnight in port. The charged battery is normally used during

manoeuvring and at slip in replace of diesel generators, whereas diesel generators are only running during the transiting phase. On the other hand, for the DE system, a single generator is running at all operation modes while, for DM system, two main engines need to run at the equivalent modes. The energy consumptions according to the proposed operational profile were determined as shown in Table 8.

Table 8

Operational profile of case ship.

Category		Transit	Manoeuvring	Slip
Daily operation hours		6	0.6	3.72
Required propulsion power (kW)		322	144	87
Hybrid	Num. of engines running	1	Batteries in operation	
	Engine load (%)	89		
	SFOC (g/kWh)	212.6		
	Fuel consumption (ton/year)	128.5		
	LO consumption (ton/year)	0.4		
	Electric consumption (MWh/year)	-	27.3	101.3
DE	Num. of engines running	1	1	1
	Engine load (%)	89 %	40 %	24 %
	SFOC (g/kWh)	212.6	240.8	266.9
	Fuel consumption (ton/year)	128.5	6.5	26.9
	LO consumption (ton/year)	0.4	0.1	0.1
DM	Num. of engines running	2	2	2
	Engine load (%)	32 %	14 %	9 %
	SFOC (g/kWh)	252.4	287.1	300.5
	Fuel consumption (ton/year)	138.0	7.0	27.1
	LO consumption (ton/year)	0.4	0.1	0.1

Annual engine maintenance costs in accordance with the engine running hours were plotted in Fig. 13. To be remarkable, the hybrid system could reduce the engine running hours by taking advantage of battery operation in replace of diesel generators at the maneuvering and slip

modes. The running time for each engine fitted to the DE and DM systems are perceived equal. Nevertheless, maintenance intervals for DM would be almost doubled because two sets of engines always need to run throughout the service. As a result, the maintenance costs for the DM system were estimated relatively higher while those of hybrids were relatively lower. As shown in Table 4, the marine engines are subject to the major overhaul at every 10,000, 20,000 and 40,000 hours, which claims high maintenance costs. For the DE and DM systems, the onboard engines were estimated at 10,000 running hours in the 4th year, 20,000 hours in 7th years and 40,000 hours in the 13th year while the diesel engines with the hybrid system were at 10,000 running hours in the 6th year, 20,000 hours in the 11th year and 40,000 hours in the 22nd year. Element flows for Case Study 1 in LabVIEW Interface were given in Fig. 14.

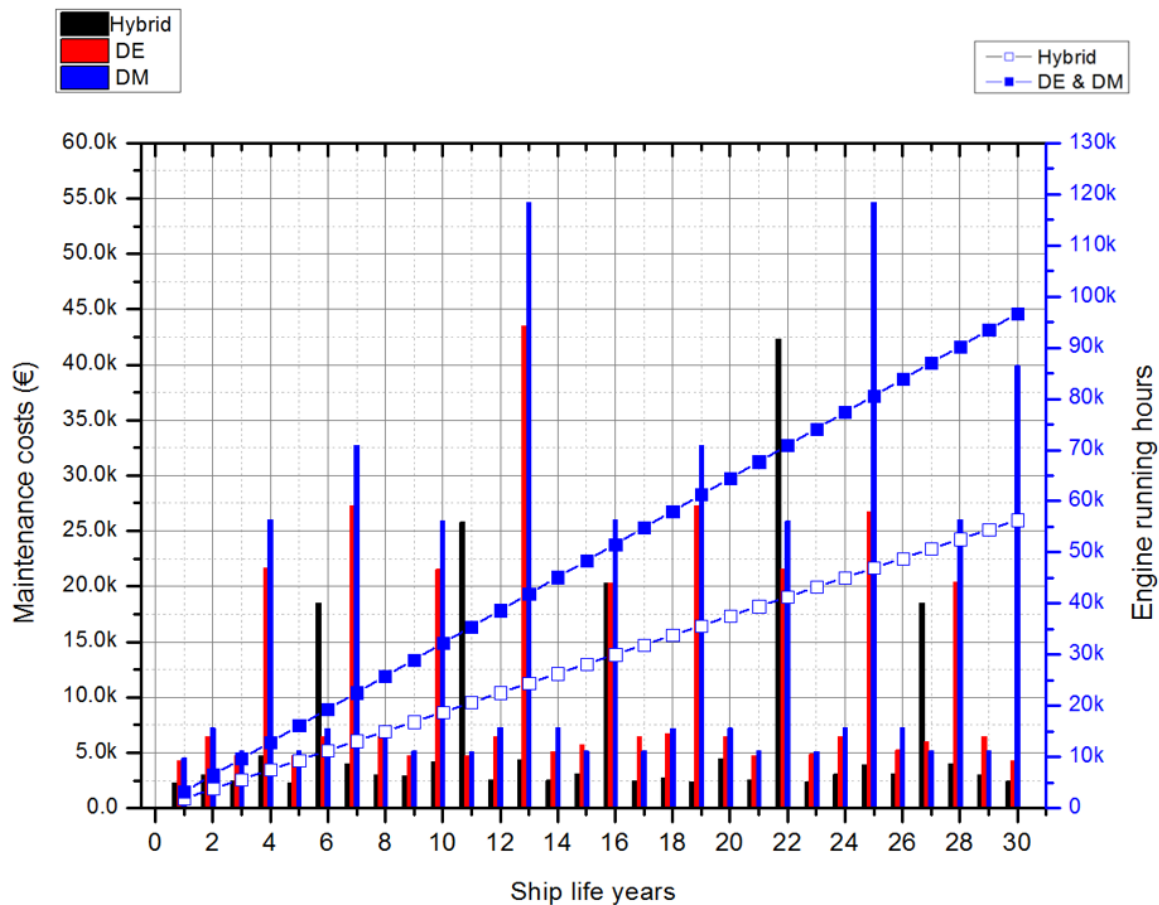


Fig. 13. Engine maintenance cost over ship life years.

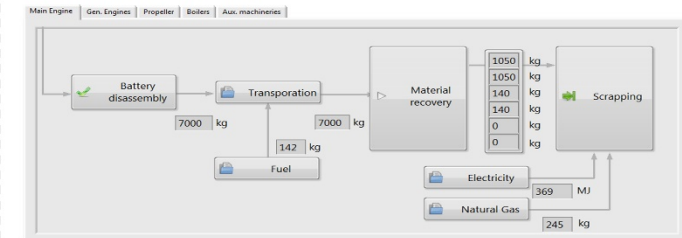
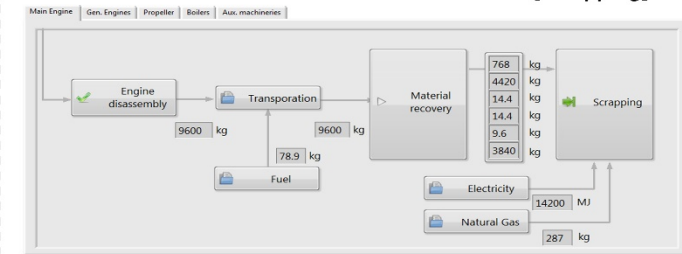
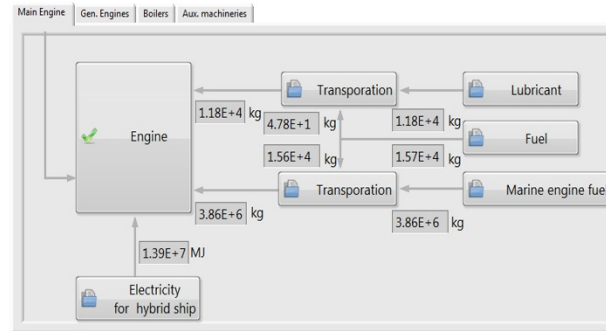
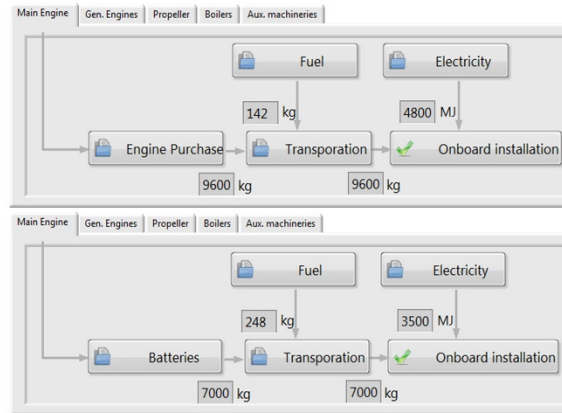


[Construction]

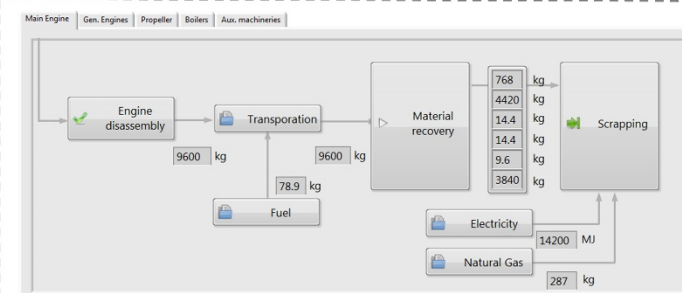
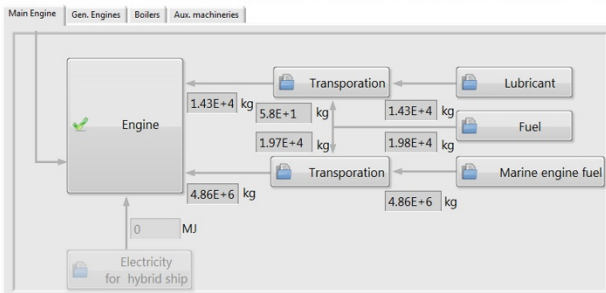
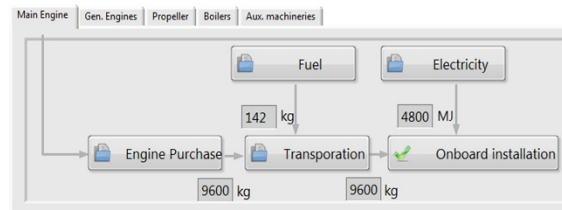
[Operation]

[Scrapping]

Hybrid



DE



DM

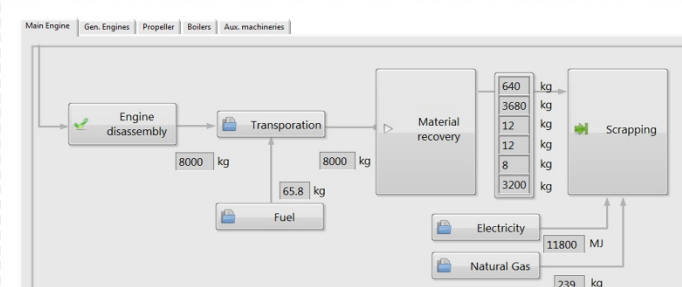
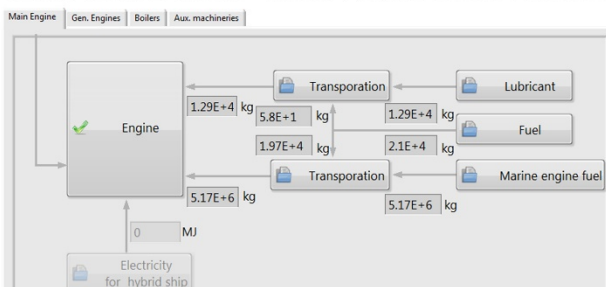
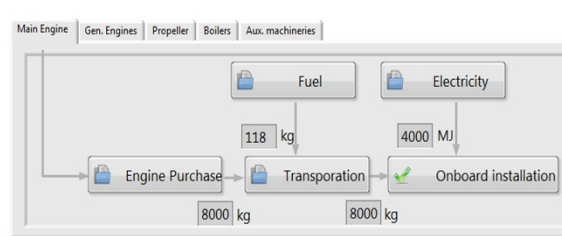


Fig. 14. Element flows for Case Study 1(in LabVIEW Interface).

3.2.2. LCA results

LCA results of the hybrid, DE and DM systems were compared in Fig. 15 and Table 9. It pointed out that the hybrid system would be the relatively cleaner option than the alternatives regarding the GWP. The same trends were also observed for the AP, EP and POCP. When using alternative options, the estimated increases in GWP were $3.5\text{E}+6$ kg for the DE system and $4.64\text{E}+6$ kg for the DM system, in AP were $2.63\text{E}+4$ kg for the DE system and $3.38\text{E}+4$ kg for the DM system, in EP were $1.13\text{E}+4$ kg for the DE system and $6.99\text{E}+4$ kg for the DM system and in POCP were $2.63\text{E}+3$ kg for the DE system and $3.67\text{E}+3$ kg for the DM system respectively. It also revealed that the operation phase would be the most influential stage since the significantly large amount of pollutants were generated at this stage. On the contrary, the environmental impacts contributed by the other three life cycle stages were negligibly small.

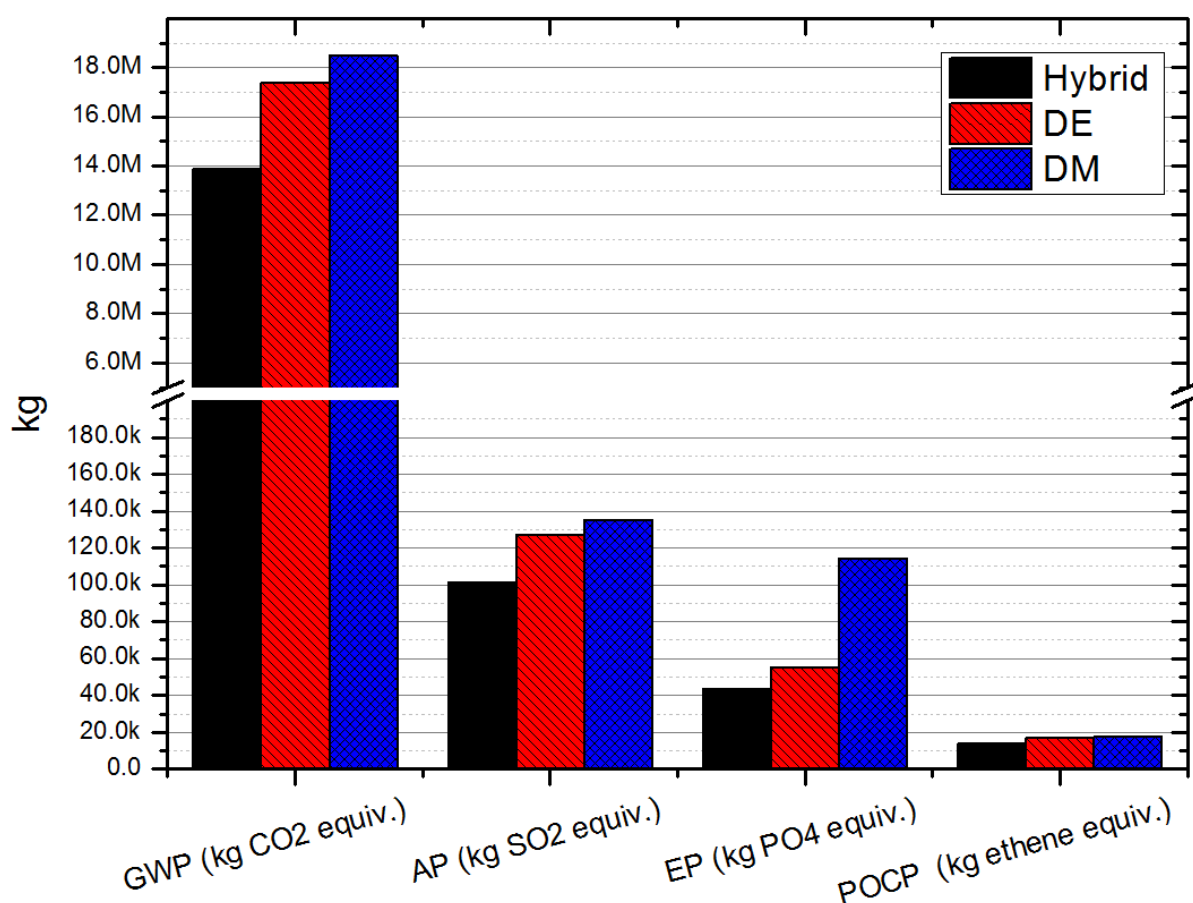


Fig. 15. Results of LCA.

To investigate the influence of different life cycle impact models on the LCA results, some other popular models - ReCiPe, TRACI and CML 2010 - were also compared to the CML 2016 model. Results were presented in the Table 9. It revealed that there were no significant

differences in terms of the GWP. On the other hand, direct comparison across the other environmental potentials do not seem permissible because some models use different units for each potential; For example, TRACI uses 'kg H+moles equivalent' for AP and 'kg N equivalent' for EP. In this context, rather than coming up with the credible process for the direct comparison, the proposed framework was intended to provide users with both CLM method as the default and other methods as options according to their preferences.

Table 9

Elementary flows for different engine configurations (unit : kg).

Pollutant		Hybrid					DE				DM				
		Construction		Operation	Scrapping		Total	Construction	Operation	Scrapping	Total	Construction	Operation	Scrapping	Total
Ammonia (to air)		2.22E-02	5.49E-02	1.19E+00	1.33E-02	2.78E-02	1.31E+00	2.22E-02	8.70E-01	1.33E-02	9.06E-01	1.85E-02	9.24E-01	1.11E-02	9.54E-01
Ammonia (to fresh water)		8.21E-05	1.01E-04	3.59E+00	2.55E-04	1.10E-04	3.59E+00	8.21E-05	4.33E+00	2.55E-04	4.33E+00	6.84E-05	4.60E+00	2.13E-04	4.60E+00
Ammonia (to sea water)		3.57E-13	3.22E-13	3.44E+00	1.02E-12	6.54E-03	3.45E+00	3.57E-13	4.33E+00	1.02E-12	4.33E+00	2.98E-13	4.60E+00	8.70E-13	4.60E+00
Carbon dioxide		5.18E+02	1.01E+03	1.35E+07	4.02E+02	5.77E+02	1.35E+07	5.18E+02	1.69E+07	4.02E+02	1.69E+07	4.32E+02	1.80E+07	3.35E+02	1.80E+07
Carbon monoxide		5.02E-01	1.63E+00	3.08E+04	5.03E-01	9.09E-01	3.08E+04	5.02E-01	3.87E+04	5.03E-01	3.87E+04	4.18E-01	4.11E+04	4.19E-01	4.11E+04
Chemical oxygen demand (to fresh water)		3.73E-02	6.94E-02	1.36E+02	6.91E-02	6.36E-02	1.36E+02	3.73E-02	1.51E+02	6.91E-02	1.51E+02	3.11E-02	1.60E+02	5.76E-02	1.60E+02
Chemical oxygen demand (to sea water)		4.90E-03	1.00E-02	6.58E+02	4.58E-03	1.45E-13	6.58E+02	4.90E-03	8.30E+02	4.58E-03	8.30E+02	4.08E-03	8.81E+02	3.82E-03	8.81E+02
Ethane		2.96E-02	6.02E-02	7.79E+02	1.23E-01	1.23E-01	7.79E+02	2.96E-02	9.80E+02	1.23E-01	9.80E+02	2.46E-02	1.04E+03	1.03E-01	1.04E+03
C2H4 (Ethene(ethylene))		1.58E-06	1.34E-06	4.36E-03	4.42E-06	2.95E-07	4.37E-03	1.58E-06	2.07E-04	4.42E-06	2.13E-04	1.36E-06	2.19E-04	3.68E-06	2.24E-04
Hydrogen chloride		9.20E-04	1.45E-03	9.37E+00	2.86E-03	1.97E-03	9.38E+00	9.20E-04	1.06E+01	2.86E-03	1.06E+01	7.67E-07	1.12E+01	2.38E-03	1.12E+01
Methane		5.96E-01	1.21E+00	1.64E+04	2.79E+00	2.72E+00	1.64E+04	5.96E-01	2.06E+04	2.79E+00	2.06E+04	4.97E-01	2.19E+04	2.32E+00	2.19E+04
Nitrogen oxides		3.65E-01	2.40E+00	3.36E+05	4.57E-01	1.38E+00	3.36E+05	3.65E-01	4.23E+05	4.57E-01	4.23E+05	3.04E-01	4.50E+05	3.81E-01	4.50E+05
Phosphate		6.90E-03	1.41E-02	9.31E+00	4.10E-03	7.19E-03	9.34E+00	6.90E-03	1.16E+01	4.10E-03	1.16E+01	5.75E-03	1.23E+01	3.42E-03	1.23E+01
Sulphur dioxide		2.02E-01	3.94E-01	7.71E+04	3.52E-01	3.69E-01	7.71E+04	2.02E-01	9.73E+04	3.52E-01	9.73E+04	1.68E-01	1.03E+05	2.94E-01	1.03E+05
Toluene		3.00E-05	5.22E-05	1.77E-01	6.81E-05	5.39E-05	1.77E-01	3.00E-05	1.97E-01	6.81E-05	1.97E-01	2.50E-05	2.09E-01	5.67E-05	2.09E-01
CML 2016	GWP (kg CO2 equiv.)	5.33E+02	1.04E+03	1.39E+07	4.72E+02	6.45E+02	1.39E+07	5.33E+02	1.74E+07	4.72E+02	1.74E+07	4.44E+02	1.85E+07	3.93E+02	1.85E+07
	AP (kg SO2 equiv.)	4.61E-01	1.76E+00	2.61E+05	6.74E-01	1.18E+00	2.61E+05	4.61E-01	3.28E+05	6.74E-01	3.28E+05	3.83E-01	3.49E+05	5.63E-01	3.49E+05
	EP (kg PO4 equiv.)	6.31E-02	3.47E-01	4.37E+04	6.99E-02	2.00E-01	4.37E+04	6.31E-02	5.50E+04	6.99E-02	5.50E+04	5.25E-02	5.85E+04	5.83E-02	1.14E+05
	POCP (kg ethene equiv.)	4.07E-02	1.45E-01	1.41E+04	7.52E-02	1.12E-01	1.41E+04	4.07E-02	1.78E+04	7.52E-02	1.78E+04	3.39E-02	1.89E+04	6.27E-02	1.89E+04
ReCipe	GWP (kg CO2 equiv.)	5.33E+02	1.01E+03	1.39E+07	4.71E+02	6.27E+02	1.39E+07	5.33E+02	1.74E+07	4.71E+02	1.74E+07	4.44E+02	1.85E+07	3.93E+02	1.85E+07
	AP (kg SO2 equiv.)	4.60E-01	1.82E+00	2.71E+05	6.41E-01	1.18E+00	2.71E+05	4.60E-01	3.42E+05	6.41E-01	3.42E+05	3.84E-01	3.64E+05	5.34E-01	3.64E+05
	EP (kg PO4 equiv.)	1.44E-01	4.54E-03	1.31E+05	1.79E-01	2.31E-03	1.31E+05	1.44E-01	1.65E+05	1.79E-01	1.65E+05	1.20E-01	1.75E+05	1.49E-01	1.75E+05

	POCP (kg NMVOC equiv.)	4.16E-01	2.46E+00	3.44E+05	5.62E-01	1.46E+00	3.44E+05	4.16E-01	4.34E+05	5.62E-01	4.34E+05	3.47E-01	4.61E+05	4.69E-01	4.61E+05
LCIA CML 2010 (Gabi default)	GWP (kg CO2 equiv.)	5.56E+02	1.01E+03	1.39E+07	4.84E+02	6.27E+02	1.39E+07	5.56E+02	1.74E+07	4.84E+02	1.74E+07	4.63E+02	1.85E+07	4.03E+02	1.85E+07
	AP (kg SO2 equiv.)	4.61E-01	1.71E+00	2.68E+05	6.75E-01	1.15E+00	2.68E+05	4.61E-01	3.38E+05	6.75E-01	3.38E+05	3.84E-01	3.59E+05	5.62E-01	3.59E+05
	EP (kg PO4 equiv.)	6.30E-02	3.38E-01	4.37E+04	6.99E-02	9.13E-01	4.37E+04	6.30E-02	5.51E+04	6.99E-02	5.51E+04	5.25E-02	5.85E+04	5.82E-02	5.85E+04
	POCP (kg ethene equiv.)	4.07E-02	1.41E-01	1.44E+04	7.52E-02	1.09E-01	1.44E+04	4.07E-02	1.82E+04	7.52E-02	1.82E+04	3.39E-02	1.94E+04	6.27E-02	1.94E+04
TRACI	GWP (kg CO2 equiv.)	5.56E+02	1.01E+03	1.39E+07	4.84E+02	6.27E+02	1.39E+07	5.56E+02	1.74E+07	4.84E+02	1.74E+07	4.63E+02	1.85E+07	4.03E+02	1.85E+07
	AP (kg H+moles equiv.)	2.70E+01	1.18E+02	1.77E+07	3.76E+01	7.47E+01	1.77E+07	2.70E+01	2.23E+07	3.76E+01	2.23E+07	2.25E+01	2.37E+07	3.13E+01	2.37E+07
	EP (kg N equiv.)	3.74E-02	1.46E-01	1.49E+04	3.55E-02	8.28E-02	1.49E+04	3.74E-02	1.88E+04	3.55E-02	1.88E+04	3.12E-02	2.00E+04	2.95E-02	2.00E+04

3.2.3. LCCA results

The results of the LCCA are presented in Fig. 16 where the accumulative costs over time for the hybrid system were plotted and compared to those of the DE and DE systems. Table 10 summarises these results as revealing that the initial costs for the hybrid system were relatively higher than the DE and DM systems. The high initial costs, however, can be compensated by relatively lower operation and maintenance costs over the ship life years. The overall benefits of the hybrid system were estimated approximately at € 12,000 compared to the DE system and up to about € 662,000 when compared to the DM system.

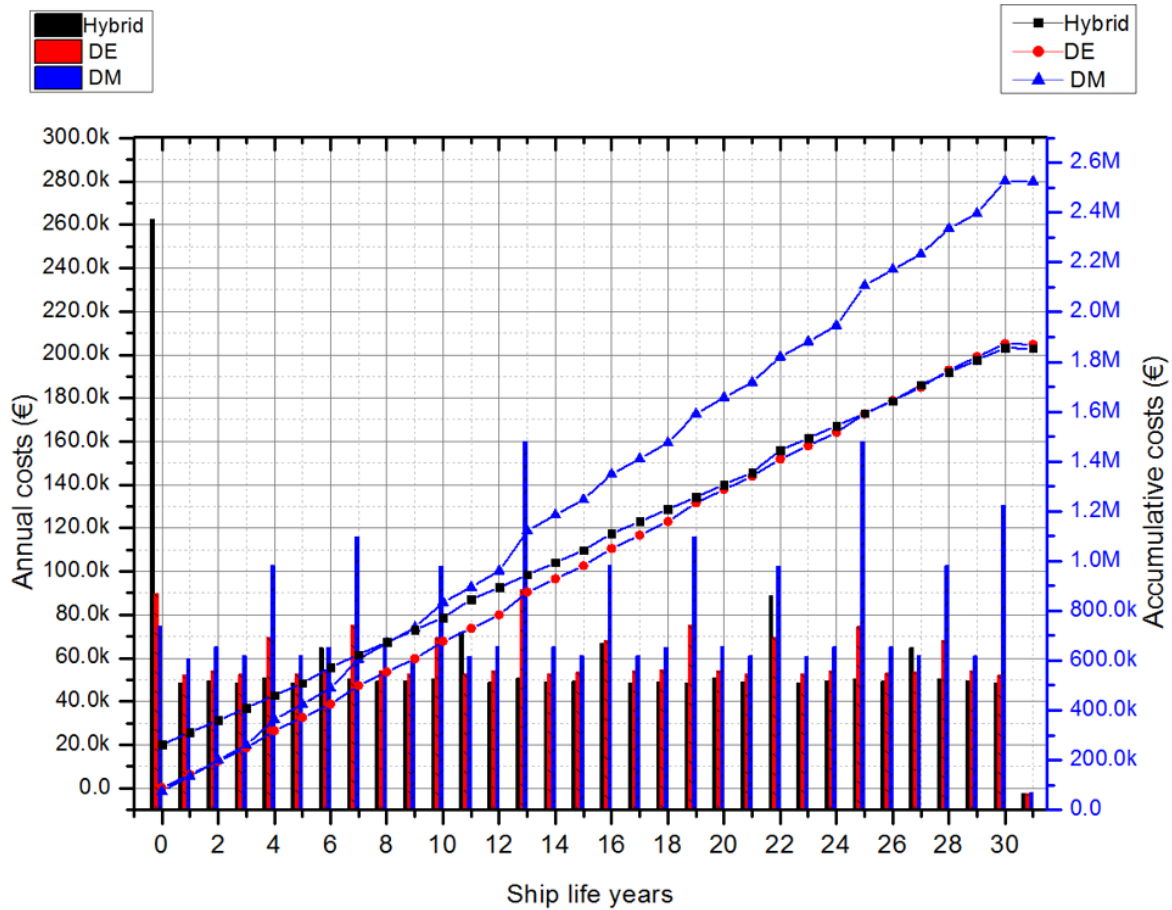


Fig. 16. Cost distribution over ship life years.

Table 10

Life cycle cost assessment for three engine configurations.

Case	Hybrid					DE					DM				
	Cons.	Operation	Main.	Scrap.	Total	Cons.	Operation	Main.	Scrap.	Total	Cons.	Operation	Main.	Scrap.	Total
Cost	263K	1,390K	203K	-2.3K	1,853.7K	89K	1435K	347K	-2.3K	1,867.7K	74K	1,523K	930K	-1.9K	2,525.1K

Unit K=1,000 €

3.2.4. Parametric analysis

In fact, hybrid batteries can be used in a wide range of operating options for the subject hybrid ferry in the long-run. In this context, the analysis carried out based on the initially fixed scenarios may bring some uncertainties in the influence of the different ways of using the hybrid system on the overall economic and environmental impacts.

In hopes of providing a general insight, two parametric cases were carried out, where the sensitivity of different scenarios in charging and using batteries was investigated in order to determine the optimal operational practice.

- P_Case 1: Charging batteries with onboard diesel engines overnight
- P_Case 2: Charging batteries through shore supply and extension of battery usage to supplement the transient operation

P_Case 1 illustrates one credible operation scenario in which the battery would be charged by the onboard diesel engine, rather than by the onshore electricity supplying facility. The charged battery would be, then, used for berthing and manoeuvring only. Meanwhile, P_Case 2 presents the maximum use of batteries where the batteries would be fully charged by the onshore facility and used for berthing, manoeuvring and the residual battery power (equivalent to cover one-hour transient operation a day) would be also used for transient phase. The results were compared in economic and environmental views as shown in Fig. 17 and Fig. 18.

LCA results show that P_Case 2, where the use of the batteries were maximum, produces the least emissions than other two scenarios. Compared to the Base case, P_Case 2 was expected to reduce $1.24\text{E}+7$ kg for the GWP, $1.68\text{E}+4$ kg for the AP, $6.64\text{E}+3$ kg for the EP, and $2.22\text{E}+3$ kg for the POCP respectively while P_Case 1 would increase in the GWP by $2.88\text{E}+6$ kg, in the EP by $9.23\text{E}+3$ kg, and in the POCP by $2.99\text{E}+3$ kg.

For LCCA, P_Case 2 appears slightly better than the other options, but the cost gap was proven insignificant. In terms of the overall costs without discount rate, P_Case 2 was expected to save

€ 24,505.4 while P_Case 2 was additionally charged with € 36,379.6, compared to the Base case. This result indicated that the minimum costs, as well as the minimum environmental impact, could be achieved with the maximum use of the batteries, as showing a clear implication of the positive relationship between the usage of hybrid and reduction in cost and emissions.

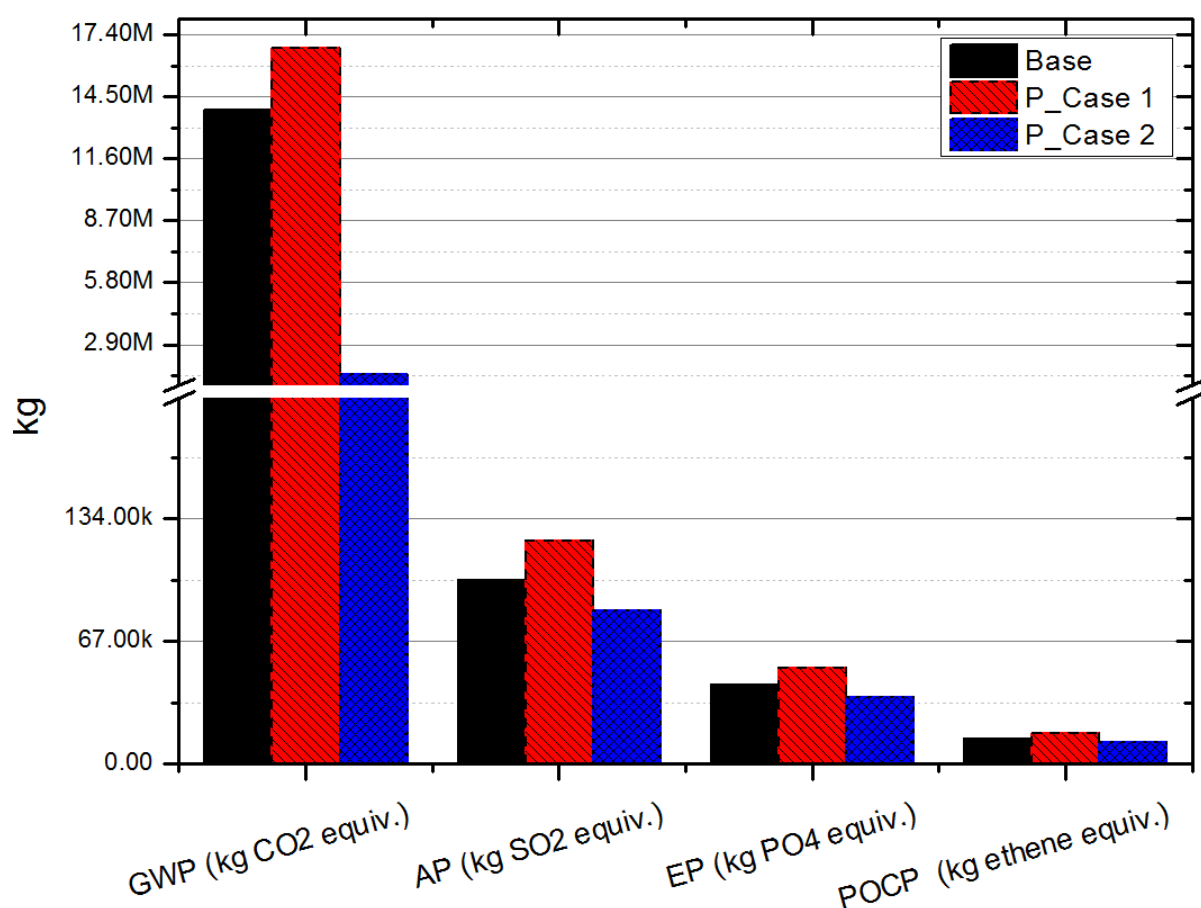


Fig. 17. Results of LCA for parametric analysis.

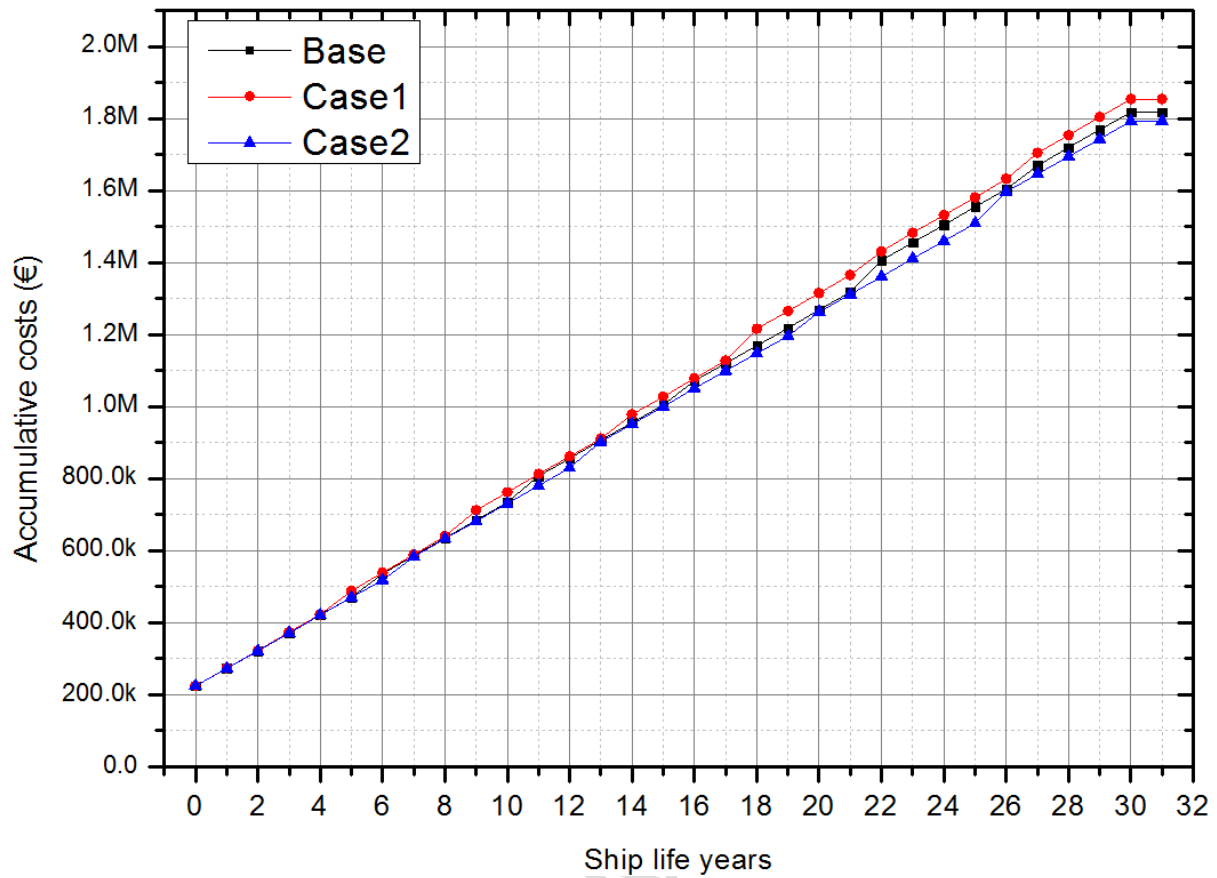


Fig. 18. Accumulative cost over ship life years.

On the other hand, the electricity for battery charge can be produced from various energy sources, possibly resulting in different levels of environmental impact. To investigate the influences of these variables, a parametric study considered six other representative energy sources: nuclear, hydroelectric, HFO, biomass, natural gas and hard coal. The LCA results are presented in Fig. 19. Not surprisingly, the gaps among the energy sources in GWP turned to be significant; conventional fossil fuels would relatively highly contribute to environmental pollutions compared to renewable and other cleaner energy sources. For the purpose of the cleaner planet overall, this result indicated that the importance of selecting the energy source for charging batteries could not be overlooked. Apart from the GWP, the differences among the energy sources in the other potentials seem negligibly small.

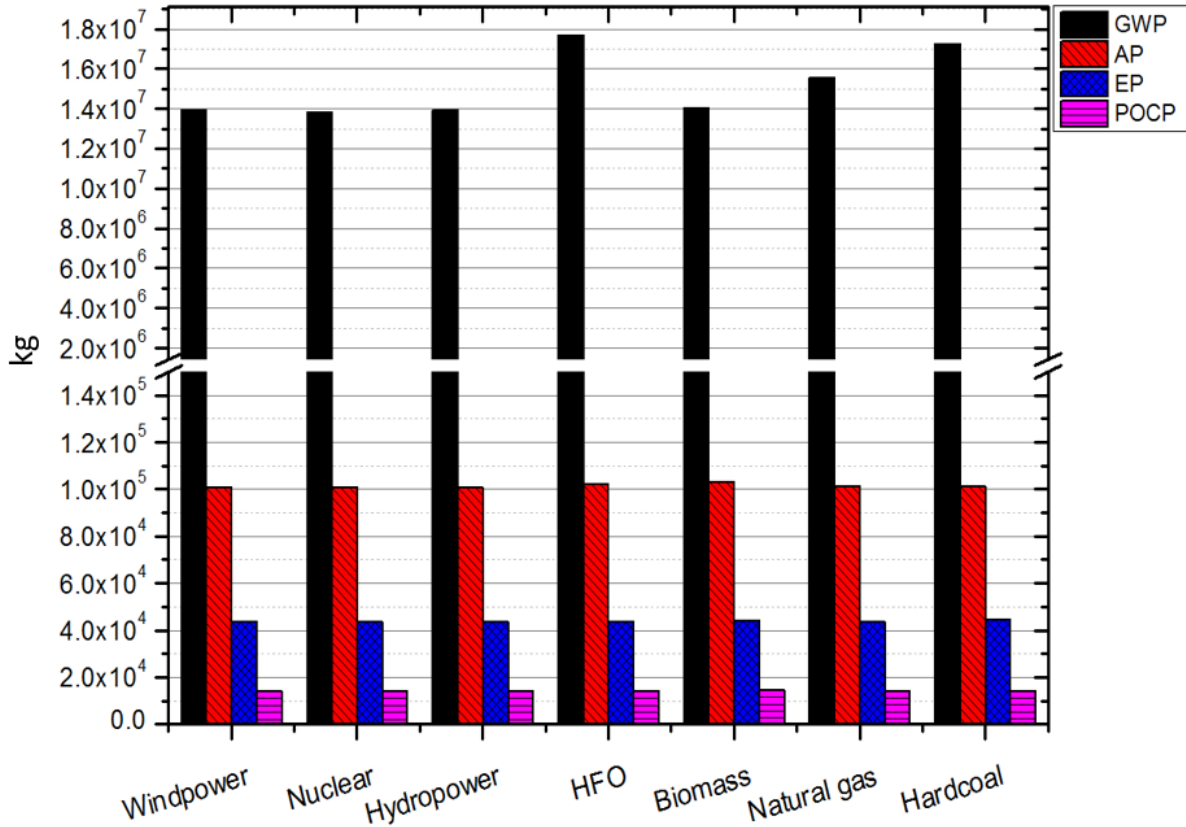


Fig. 19. Results of LCA for different energy sources to produce electricity.

3.3. Case study 2: Optimum engine configuration for offshore tug vessel

The purpose of this case study was to optimise engine selection and its application on an offshore tug vessel currently under design at a Turkish shipyard. This goal was to be achieved by comparing two different conceptual engine configurations applicable to the case ship. A focus was placed on evaluating the cost-effectiveness and environmental-friendliness over the ship's potential life ranging from construction, operation, maintenance to scrapping.

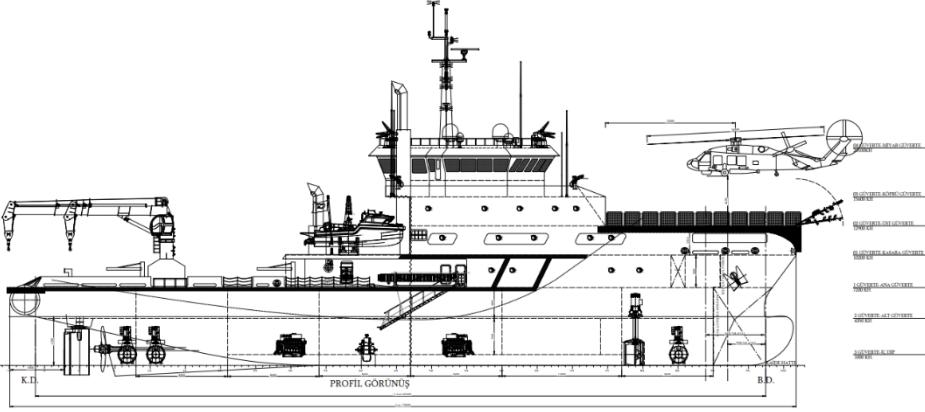
3.3.1. Case ship

The general description of the case ship is outlined in Table 11, whereas Fig. 20 shows the propulsion power system configurations. At the conceptual design stage, two practicable configurations of the propulsion power system have been proposed by the designer. The initial option for main engine configuration would install two sets of 4,500 kW engines and each of them is directly connected to the propeller shaft (hereafter referred to as 'Base' option). The

other option would be the arrangement of four sets of 2,220 kW engines and every two sets of them are connected to a single shaft via a gearbox (hereafter referred to as ‘Alternative’ option).

Table 11

Specification of case ship (Dearsan, 2017).

		
Length × Breadth × Depth	72.6 m × 16.0 m × 7.2 m	
Displacement (t)	2,270 tons (Steel)	
Main engine	Base	Alternative
	MAN 4,500 kW × 720 RPM × 2 sets (each weight 51 tons)	MAN 2,220 kW × 1900 RPM × 4 sets (each weight 8.5 tons)

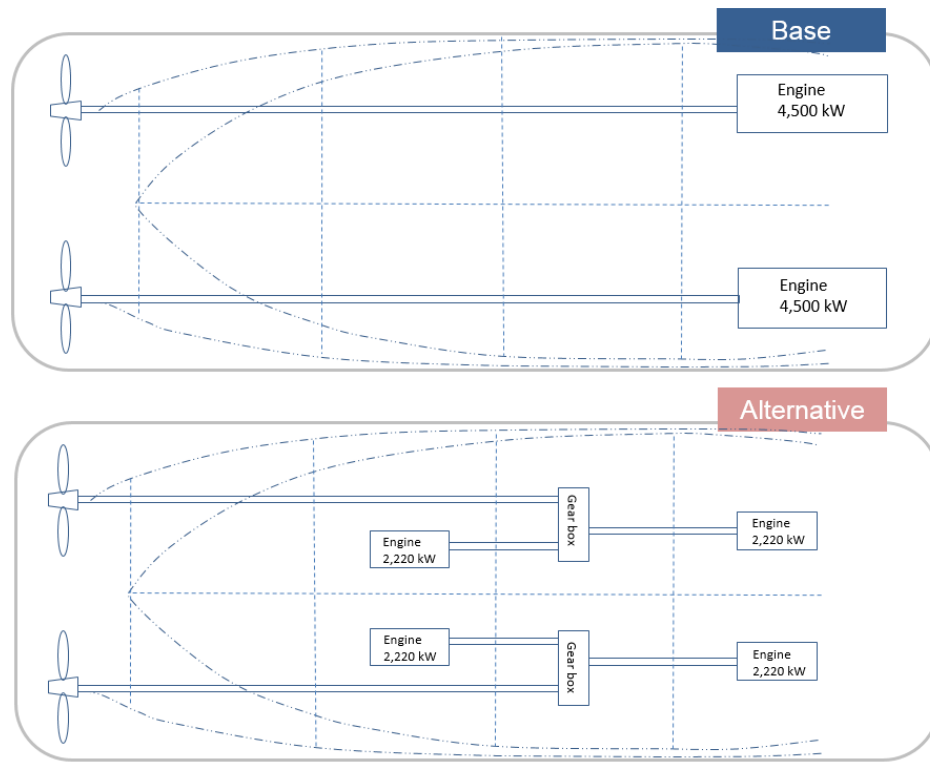


Fig. 20. Layout of propulsion power system configurations.

For construction phase, by courtesy of the engine manufacturer, MAN Diesel and Turbo Ltd, engine prices were estimated at € 373,500 for a set of 4,500 kW diesel engine and € 182,600 for a set of 2,220 kW diesel engine. Based on the proposed operational profile for the case ship, the propulsion powers required for various ship speeds were estimated, and the fuel consumption and emissions were quantified in three different modes: 14, 16 and 18 knots. The diesel engines were kept out of use in port and DP mode. Operational costs and emissions were calculated in accordance with Table 12 which delivers the proposed operational profile and fuel and lubricant consumptions.

Table 12

Fuel and lubricant consumption based on engine operation profile.

Category		Port	14 knot	16 knot	18 knot	DP
Operation (%)		20.0	60.0	10.0	5.0	5.0
Time (hrs/year)		1,752	5,256	876	438	438
Propulsion power (kW)		0.0	1767.0	3451.0	5885.0	0.0
Base	Num. of Engines running	Engine Stop	2	2	2	Engine Stop
	Load (%)		19.6	38.3	65.4	
	SFOC (g/kWh)		275.9	243.2	216.2	

	Fuel consumption (ton/year)		2562.7	735.1	557.4	
	LO consumption (ton/year)		6.0	2.0	1.7	
Alter.	Num. of Engines	Engine Stop	2	2	4	Engine Stop
	Load (%)		39.8	77.7	66.3	
	SFOC (g/kWh)		241.1	212.0	215.8	
	Fuel consumption (tons/year)		2239.3	640.8	556.2	
	LO consumption (tons/year)		6.0	2.0	1.7	

Fig. 21 shows annual maintenance costs in consideration of the engine running-hour. What stands out from the operating profile was that all engines (two sets) should operate at all speeds for Base option; however, for Alternative option, all engines (four sets) were in operation at 18 knots, but only two engines run at 12 and 14 knots. This provides economic benefits to the engine maintenance phase as plotted in the figure. By taking advantage of the flexibility in engine operation, Alternative option can achieve significantly less engine running hours than Base option. Consequently, lower maintenance costs were claimed. Element flows for Case Study 2 in the LabVIEW interface were given in Fig. 22.

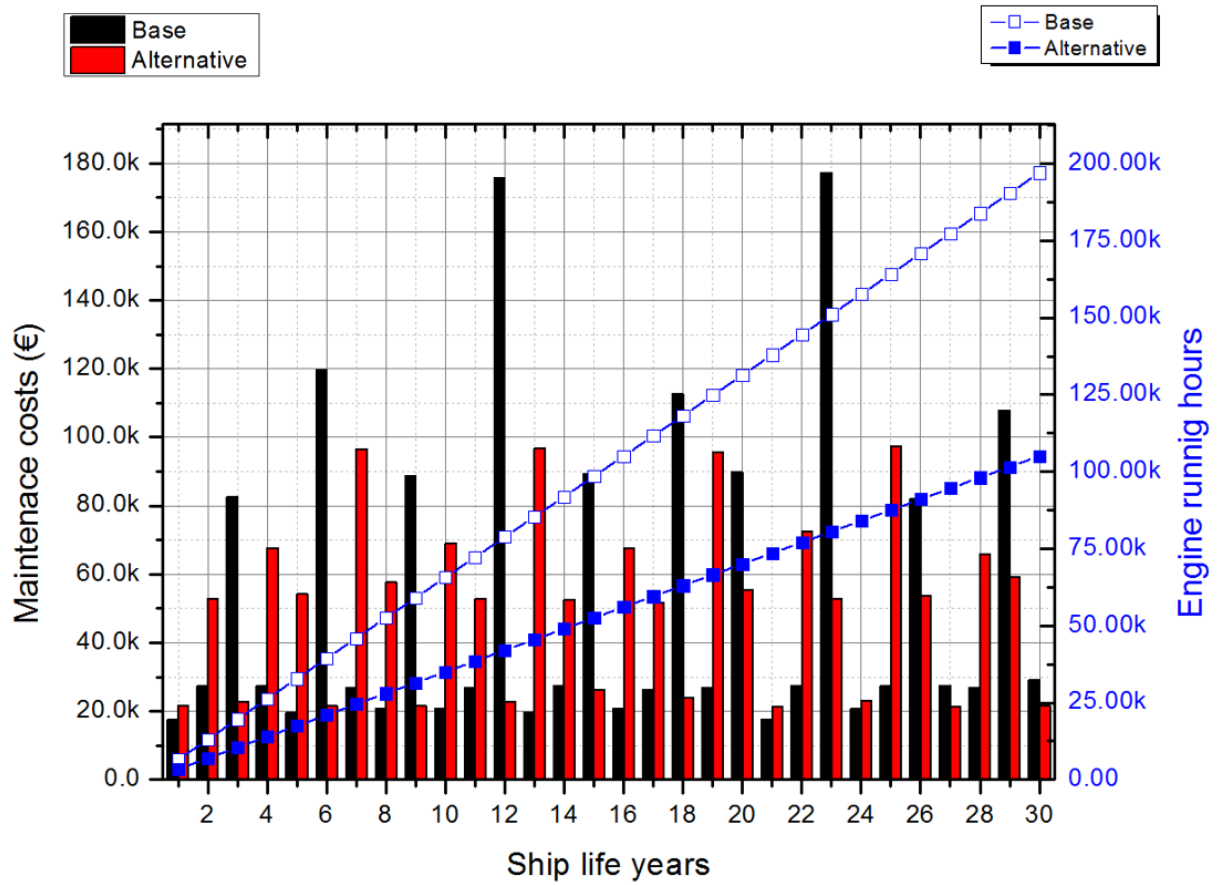


Fig. 21. Running hours and maintenance costs over ship life years.

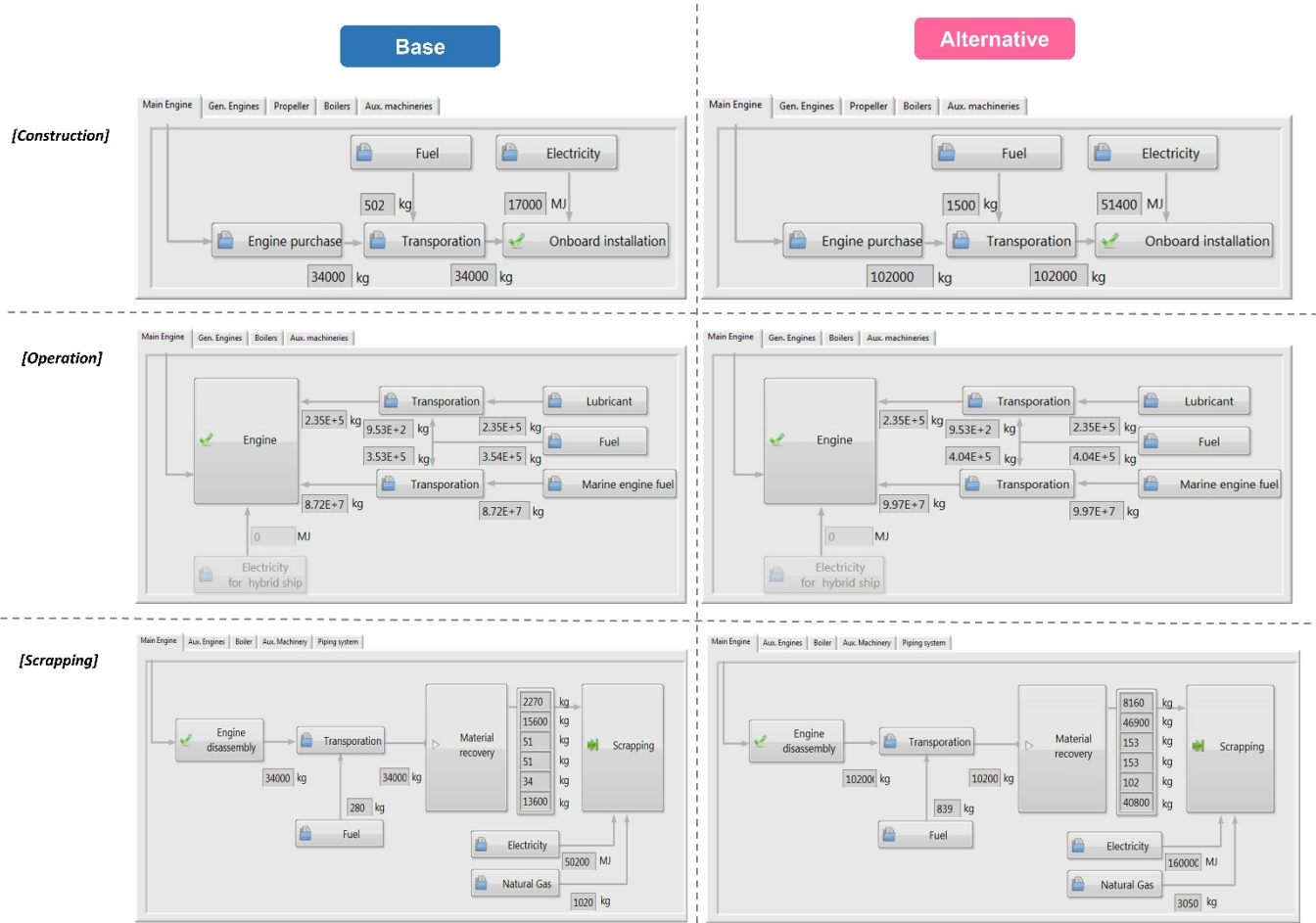


Fig. 22. Element flow for Case Study 2 (in LabVIEW interface).

3.3.2. LCA results

LCA results, presented in Table 13, revealed that Alternative option would be more advisable than Base option. This was because the environmental impact for Alternative option was relatively smaller than that of the Base option. Based on the CML model, the gaps between the two option in the GWP was $4.53\text{E}+7$ kg, in the AP was $8.81\text{E}+5$ kg, in the EP was $1.42\text{E}+5$ kg and in the POCP was $4.73\text{E}+4$ kg. The same trend with the Case study 1 was observed that the operation phase would be the dominant life stage. For the sensitivity in the selection of life cycle impact models, the LCA was also assessed with different models: Recipe, LCIA (Gabi default), TRACI. Similar to Case study 1, Results of the sensitivity analysis suggested there was no significant deviation among the impact models.

Table 13

Elementary flows of different engine configurations

Pollutants		Base				Alternative			
		Construction	Operation	Scrapping	Total	Construction	Operation	Scrapping	Total
Ammonia (to air)		2.36E-01	1.78E+01	1.41E-01	1.82E+01	7.87E-02	1.56E+01	4.70E-02	1.57E+01
Ammonia (to fresh water)		8.72E-04	8.88E+01	2.71E-03	8.88E+01	2.91E-04	7.77E+01	9.03E-04	7.77E+01
Ammonia (to sea water)		3.80E-12	8.88E+01	1.11E-11	8.88E+01	1.27E-12	7.77E+01	3.70E-12	7.77E+01
Carbon dioxide		5.51E+03	3.47E+08	4.27E+03	3.47E+08	1.84E+03	3.03E+08	1.47E+03	3.03E+08
Carbon monoxide		5.33E+00	7.93E+05	5.34E+00	7.93E+05	1.78E-01	6.93E+05	6.12E-02	6.93E+05
Chemical oxygen demand (to fresh water)		3.97E-01	3.09E+03	7.35E-01	3.09E+03	1.31E-01	2.70E+03	2.45E-01	2.70E+03
Chemical oxygen demand (to sea water)		5.20E-02	1.70E+04	4.86E-02	1.70E+04	1.73E-02	1.49E+04	1.62E-02	1.49E+04
Ethane		3.14E-01	2.01E+04	1.31E+00	2.01E+04	1.05E-01	1.76E+04	4.37E-01	1.76E+04
C2H4 (Ethene(ethylene))		1.68E-05	4.23E-03	4.68E-05	4.29E-03	5.58E-06	3.70E-03	1.56E-05	3.72E-03
Hydrogen chloride		9.78E-03	2.16E+02	3.03E-02	2.16E+02	3.26E-03	1.89E+02	1.01E-02	1.89E+02
Methane		6.34E+00	4.23E+05	2.96E+01	4.23E+05	2.11E+00	3.70E+05	9.87E+00	3.70E+05
Nitrogen oxides		3.88E+00	8.68E+06	4.86E+00	8.68E+06	1.29E+00	7.59E+06	1.62E+00	7.59E+06
Phosphate		7.33E-02	2.37E+02	4.35E-02	2.37E+02	2.44E-02	2.07E+02	1.45E-02	2.07E+02
Sulphur dioxide		2.14E+00	2.16E+06	3.75E+00	2.16E+06	7.15E-01	1.88E+06	1.25E+00	1.88E+06
Toluene		3.19E-04	4.03E+00	7.23E-04	4.03E+00	1.06E-04	3.53E+00	2.41E-04	3.53E+00
CML 2016	GWP (kg CO2 equiv.)	5.67E+03	3.58E+08	5.01E+03	3.58E+08	1.89E+03	3.12E+08	1.72E+03	3.12E+08
	AP (kg SO2 equiv.)	4.89E+00	6.93E+06	7.18E+00	6.93E+06	1.63E+00	6.05E+06	2.39E+00	6.05E+06
	EP (kg PO4 equiv.)	6.70E-01	1.13E+06	7.43E-01	1.13E+06	2.23E-01	9.87E+05	2.48E-01	9.87E+05
	POCP (kg ethane equiv.)	4.32E-01	3.73E+05	8.00E-01	3.73E+05	1.01E-01	3.26E+05	2.20E-01	3.26E+05
ReCipe	GWP (kg CO2 equiv.)	5.67E+03	3.11E+08	5.01E+03	3.11E+08	1.89E+03	3.13E+08	1.67E+03	3.13E+08
	AP (kg SO2 equiv.)	4.89E+00	7.02E+06	6.81E+00	7.02E+06	1.36E+00	6.13E+06	2.27E+00	6.13E+06
	EP (kg N equiv.)	1.53E+00	3.38E+06	1.90E+00	3.38E+06	5.10E-01	2.95E+06	6.34E-01	2.95E+06
	POCP (kg NMVOC equiv.)	4.42E+00	8.90E+06	5.97E+00	8.90E+06	1.47E+00	7.78E+06	1.99E+00	7.78E+06
LCIA CML 2010 (Gabi default)	GWP (kg CO2 equiv.)	5.91E+03	3.58E+08	5.14E+03	3.58E+08	1.97E+03	3.18E+08	1.71E+03	3.18E+08
	AP (kg SO2 equiv.)	4.90E+00	6.93E+06	7.17E+00	6.93E+06	1.63E+00	6.06E+06	2.39E+00	6.06E+06
	EP (kg PO4 equiv.)	6.70E-01	1.13E+06	7.42E-01	1.13E+06	2.23E-01	9.87E+05	2.47E-01	9.87E+05
	POCP (kg ethane equiv.)	4.32E-01	3.73E+05	7.99E-01	3.73E+05	1.44E-01	3.26E+05	2.66E-01	3.26E+05
TRACI	GWP (kg CO2 equiv.)	5.91E+03	3.58E+08	5.13E+03	3.58E+08	1.97E+03	3.13E+08	1.71E+03	3.13E+08
	AP (kg H+ moles equiv.)	2.87E+02	4.57E+08	3.99E+02	4.57E+08	9.57E+01	3.99E+08	1.33E+02	3.99E+08
	EP (kg N equiv.)	3.97E-01	3.87E+00	3.77E-01	4.64E+00	1.32E-01	3.37E+05	1.26E-01	3.37E+05

3.3.3. LCCA results

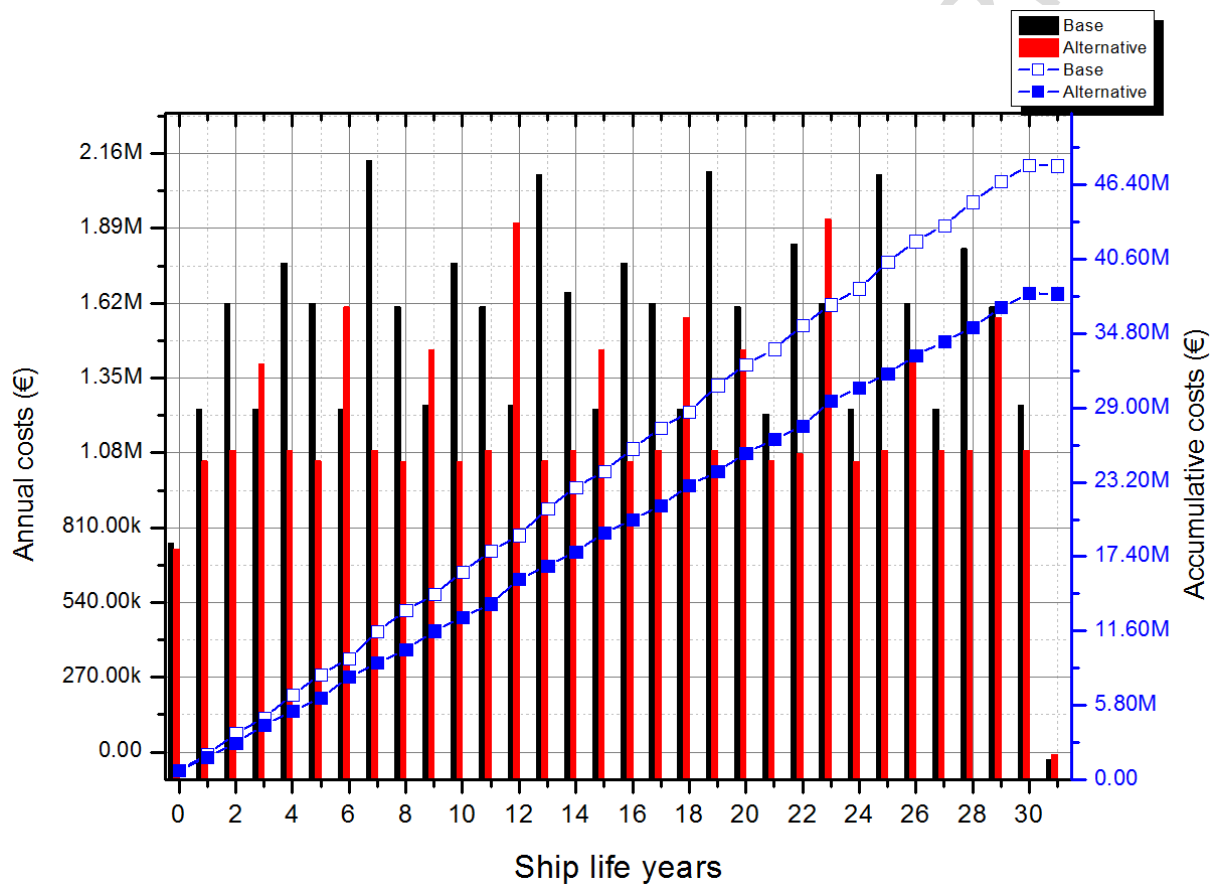
The LCCA results are shown in Table 14 and Fig. 23. In the same line with the LCA results, it can be seen that Alternative option granting a relatively low cost would be more optimistic than Base option; approximately € 3,590,000 could be saved when the alternative case is applied.

Table 14

Life cycle cost assessment for two engine configurations.

Case	Base					Alternative				
Phase	Cons.	Operation	Main.	Scrap.	Total	Cons.	Operation	Main.	Scrap.	Total
Cost	752K	33,607K	13,557K	-25K	47,892K	733K	29,955K	7,237K	-8.4K	37,917K

Unit K=1,000 Euro

**Fig. 23.** Cost distribution over ship life years.

3.3.4. Parametric study

Given that the case ship may be assigned to different operating conditions in the long-run, two additional scenarios have been proposed in efforts to investigate the sensitivity of the different operating conditions on the economic and environmental impacts. In this context, a parametric study was carried out, exploring the relationship between the speed and economic/environmental impacts by developing two counterpart cases: P_Case 1 for operation at minimum speed, whereas P_Case 2 for operation at maximum speed.

- P_Case 1: the speed of case ship is kept at 14 knots to meet a slow steaming strategy.
- P_Case 2: case ship keeps sailing at the full service speed of 19 knots.

Table 15 shows the revised operating profile for the case vessel.

Table 15

Operational profile of case ship.

P_Case 1	Category	Port	14 knots	DP
	Operation (%)	20.0	60.0	5.0
	Time (hrs/year)	1,502	6,820	438
	Propulsion power (kW)	0.0	1,767.0	0.0
P_Case 2	Category	Port	19 knots	DP
	Operation (%)	34.4	60.6	5.0
	Time (hrs/year)	3,017	5,305	438
	Propulsion power (kW)	0.0	7,922	0.0

In Fig. 24, LCA results showed that P_Case 1 had a relatively low emission impact while P_Case 2 had a higher overall emission impact when engaged in full-service speed. It demonstrated the common knowledge that the operating ships at low speed would be more desirable in terms of cost-benefit and environmental impacts. The same trend for the LCCA was observed in Fig. 25, pointing out that the small engine configuration would be more profitable when the engines were operating at low loads rather than full load. It was because that the full speed operation (P_Case 2) claimed higher economic expenses mainly from fuel consumptions and maintenance costs, compared to slow-steaming mode (P_Case 1) or original operational profile.

On the other hand, research findings also revealed that P_Case 2 would be more advantageous in both economy and environmental perseverance, providing a clear implication of the negative relationship of the operation speed with the reduction in cost and emission levels.

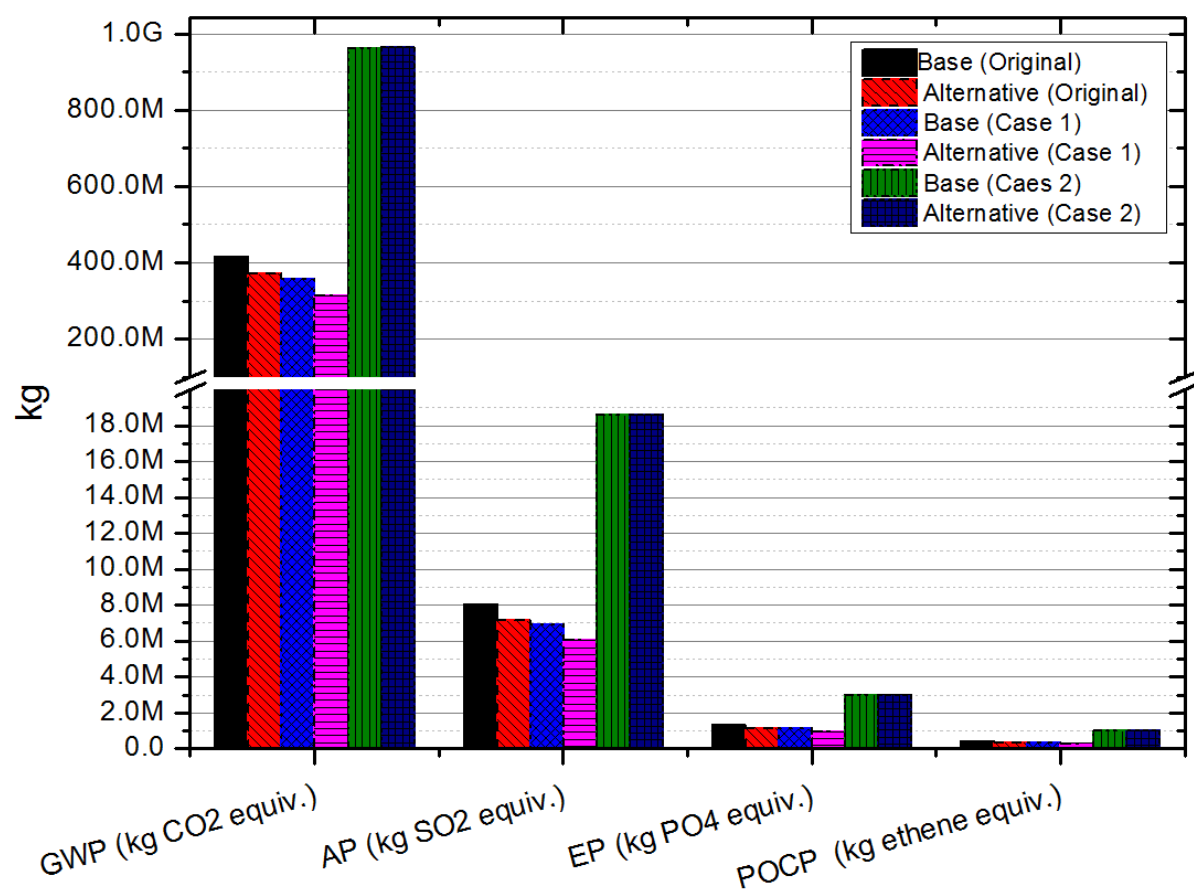


Fig. 24. Results of LCA for parametric analysis.

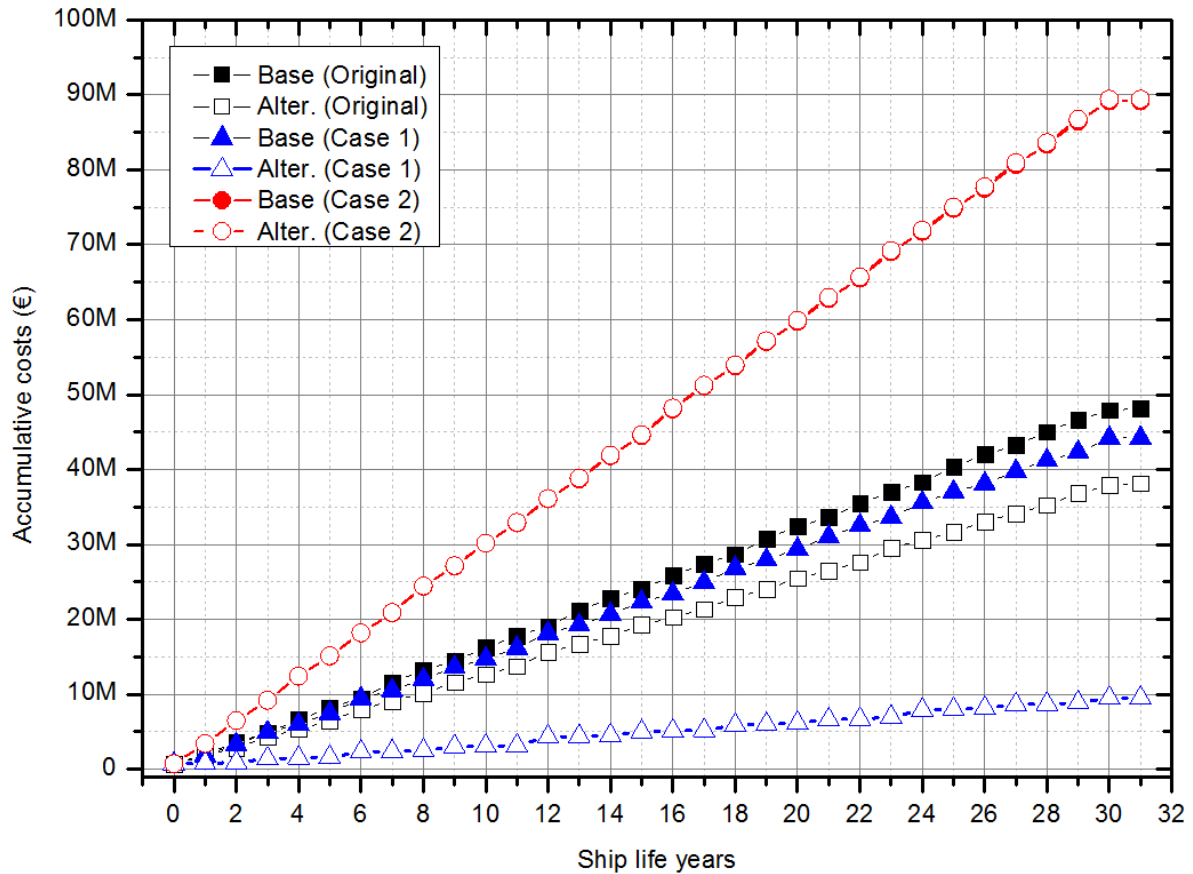


Fig. 25. Accumulative cost over ship life years.

4. Discussion

The marine industry is still far away from using the LCA and LCCA techniques albeit they are necessary for optimal decision making. In particular, the lack of trained staff and relevant tools has been a long-lasting obstacle for small and medium-sized entrepreneurs (SMEs) to apply those techniques to industry-specific cases.

In this context, this research was originally inspired by the needs of naval architects, shipyards, and ship-owners who strive to find ways to survive in competitive markets where they must improve cycle time and capacity to reduce design and production costs. Hence, this paper was intended to help SMEs to construct ships in more reliable manners, while compliant with stringent requirements to preserve the marine environment.

This research can be regarded as a preliminary study to provide shipyards, ship-owners, and researchers with a toolkit that will facilitate such analyses by modulating life cycle processes of a general ship. Then, the methods of LCA and LCCA were implemented in the designed modules individually. Hence, the module-based LCA and LCCA may allow users disregard

the process of modelling and integration of complex formula with outsource database. Instead, it may offer a significant flexibility in selecting modules for the LCA and LCCA, depending on the scope of work.

By the requests of shipyards, this idea was applied to two actual projects (case studies 1 and 2) through which the effectiveness of the proposed framework was demonstrated. The case studies also suggested that LCA might be useful for evaluating the environmental impact of ships.

This research also showed that the possibility of LCA to replace the current IMO guidance on estimating emissions as it could deal with the environmental impacts of the ship much more extensively and precisely.

The results of the LCCA showed the importance of attaining the long-term view of cost estimation in the marine industry where ship-owners and the builders tend to have a short-term view of cost estimation. This research considered the discount rate was zero in order to purely compare the nominal cost of the system options. That means the analysis becomes insensitive to the time passage. Given that the monetary value of time and the discount rate would significantly contribute to increasing actual costs, uncertainty analysis with various discount rates may be necessary for deeper understanding of cost estimations in later stage. Therefore, LCCA may help them to extend their economic view to make proper decisions in long run.

The data used in this paper was stored in a database which has been developed with vigorous efforts by industrial and academic partner groups across Europe. It contains key information on various ship activities/processes across the ship lifecycle such as shipbuilding process, design, operation, maintenance, retrofitting and scrapping. This paper, regarding LCCA, referred to the cost information associated with ship products, systems, equipment and materials as well as the energy consumption, labour forces etc. For LCA, it borrowed environmental data on types of emissions and their quantitative levels for particular ship activities. Information delivered in Tables 1 - 6 and data descriptions in Section 3 were all included in this database. This research has also shown that the direct connection of extensive data resources with the framework proposed in this paper would facilitate the LCA and LCCA.

The purpose of this paper was to introduce an effective framework for LCA and LCCA applicable to the marine industry in hopes of helping SMEs to make a proper decision at early ship design stage. To investigate the effectiveness of the proposed framework, this paper applied it to two industry-tailored case studies; the main objective of these case studies was to identify the optimal propulsion systems across several possible choices from economic and

environmental perspectives. It is believed that the modular platform introduced in this paper can be directly applied to the ship contract or initial design stages where rapid, but, reliable decision-making is imperative. Although these case studies were conducted simply due to the industrial needs, it does not mean that the application of the proposed framework is limited to this boundary work. It may be also worthy of emphasizing that the application of the proposed ideas with module-based the LCA and LCCA can be extended to a wide variety of areas where such analyses are immature. For future works, the extension of this application will be necessary.

5. Concluding remark

Based on the work discussed in the foregoing, the research findings are summarised as below:

- (1) The effectiveness of the new lifecycle platform for optimal selection of ship designs was demonstrated in a way that the module-based analysis can greatly simplify the LCA and LCCA by eliminating the user modelling/analytic procedure, thereby speeding up the decision-making process;
- (2) The advantages of hybrid system (battery system) were demonstrated through Case study 1. LCA results indicated that the hybrid system could be an attractive means towards a greener maritime industry. Moreover, the high cost-effectiveness of hybrid systems compared to conventional ones was also proven in LCCA;
- (3) Case study 2 revealed the installations of several sets of smaller engines were more desirable than two sets of medium or large engines in both cost and environment aspects;
- (4) Given lifespan of ships, operation phase (the longest period, 30 years) was proven as the most dominant stage in terms of determining the holistic LCA and LCCA results;
- (5) The research results from both case studies provided readers with insights into the importance of LCA and LCCA for the marine industry to take a step forward.

Acknowledgement

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Highlights

- Effectiveness of the new life cycle framework for optimal marine propulsion system selection was demonstrated.
- Application of modularity principle into life cycle ship design was proven rapid and effective.
- Effectiveness of iterative process to compare different design options was demonstrated.
- Excellence of a hybrid ship over conventional ones was demonstrated.
- It was demonstrated that smaller engines are more beneficial than larger engines.